Neutron Interaction with Matter: Basics for Neutron Detection

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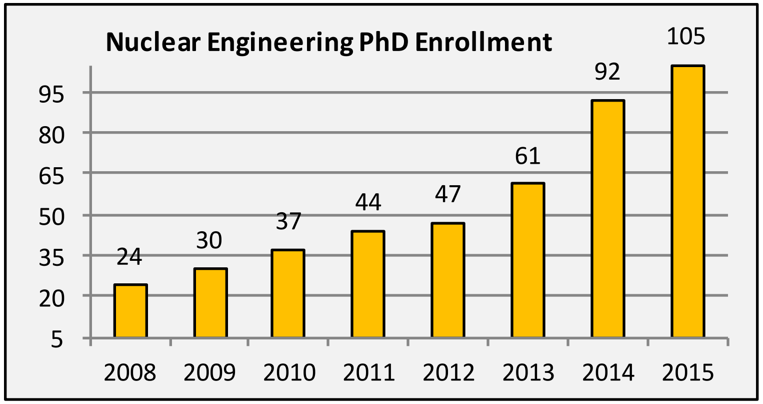
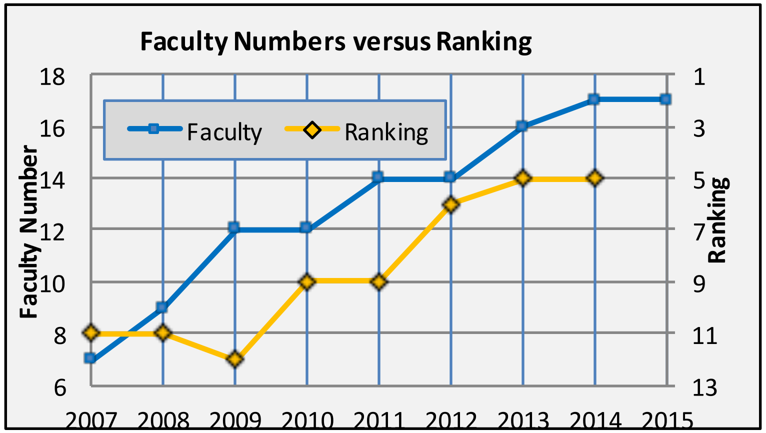
NDRA 2016

UTK Nuclear Engineering

- Founded in 1957, oldest NE Department
  - Top ranked in US News & World Report
  - Close partnership with Oak Ridge National Laboratory, Y-12, and local industry
- Offer BS, MS, PhD degrees and three graduate certificates
- Research areas
  - Nuclear Reactor Fuels and Materials
  - Nuclear Security
  - Nuclear Instrumentation
  - Radiological Sciences and Health Physics
  - I&C, Reliability, and Safety
  - Nuclear Fuel Cycle
  - Advanced Modeling and Simulation
  - Nuclear Fusion Technologies





ORNL connections

- Nuclear Materials Detection and Characterization Group
    - Passive gamma and neutron imaging
    - Tagged neutron interrogation, multi-modal imaging
    - Neutron and gamma detection (handhelds to trailer-based platforms)
- Safeguards Technology Group
    - Nuclear materials characterization/passive assay (especially uranium)
- Neutron Sciences Directorate
    - He-3 replacement technologies
    - High resolution instrumentation for imaging/neutron science

UTK research program description

- Much of my group's work comprises R&D of radiation instrumentation for nuclear nonproliferation technologies
- A major focus is materials and sensor system development for neutron, gamma ray, and muon imaging, as well as new theory, methods and algorithms research for improved, *quantitative* analysis of the associated data
- Multidisciplinary work (new materials to systems and algorithms) conducted in lab/office space at UTK and ORNL
- Research supported by DHS, DOE, DoD, NSF, UT-Battelle, medical imaging companies (more info at rir.utk.edu)
- At present, group consists of 18 student and staff researchers at graduate level or above (12 men, 6 women); adding 4 more grads
- 25 peer reviewed publications since 2012, mainly in IEEE TNS & NIM A; 8 PhDs graduated

A bit about me

- PhD Nuclear Engineering and Radiological Science, **University of Michigan, Ann Arbor, MI** 2007 (MSE in 2004)
- Undergraduate work in physics, mathematics, and humanities (Valparaiso University, 1999)
- US. Naval Officer (Nuclear program, Office of Naval Research) 1999-2007; served out of in Charleston, SC, and Chicago, IL
- UTK and ORNL faculty appointment since Jan. 2008, became tenured faculty in 2014
- Have taught college level classes in physics, nuclear reactor principles and operations, nuclear power for non-majors, radiation instrumentation, radiation detection and measurement, characterization/assay of nuclear materials since 2000
- Married with two daughters, ages 12 and 16
- Hometown near Ann Arbor, Michigan
- First time in Italy…

Topics for this morning

- History and nuclear basics
- Neutron interactions
- Detection basics
- Slow neutron detection
- Fast neutron detection
- More relevant cross sections
- Summary

Acknowledgements

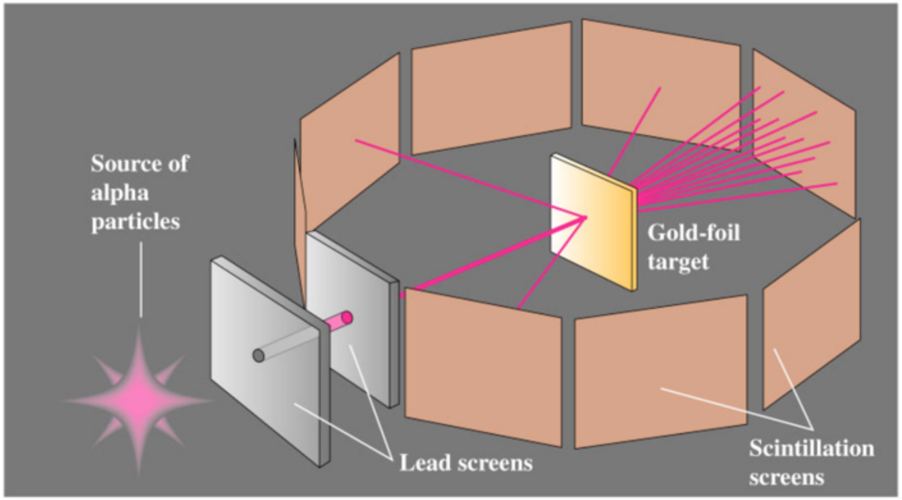
- Dr. Zane Bell, ORNL, especially detailed look at cross section data
- Prof. Kate Jones, UTK Nuclear Physics, experimental nuclear physics material enhanced these notes
- The late Prof. Glenn Knoll's textbook, 4th edition, radiation detector basics

History and nuclear basics

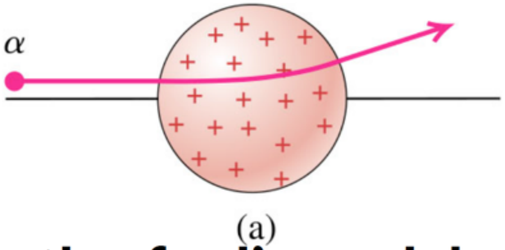
The state of early 20th century physics

- Electricity – well known by end of the 19th century
- Cathode rays discovered – negative charge
- X rays – caused by interactions of cathode rays with matter
- Periodic table known – concept of atomic number
- What was known about the nucleus?

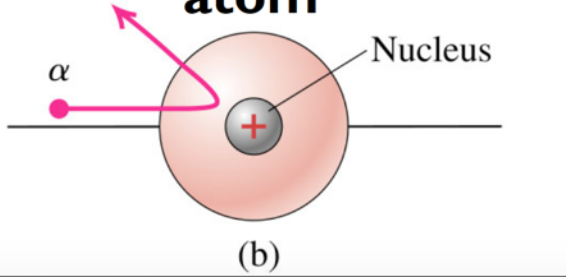
Rutherford scattering experiment



Thomson's model of atom



Rutherford's model of atom



"It was almost as incredible as if you had fired a 15 inch shell at a piece of tissue paper and it came back and hit you"

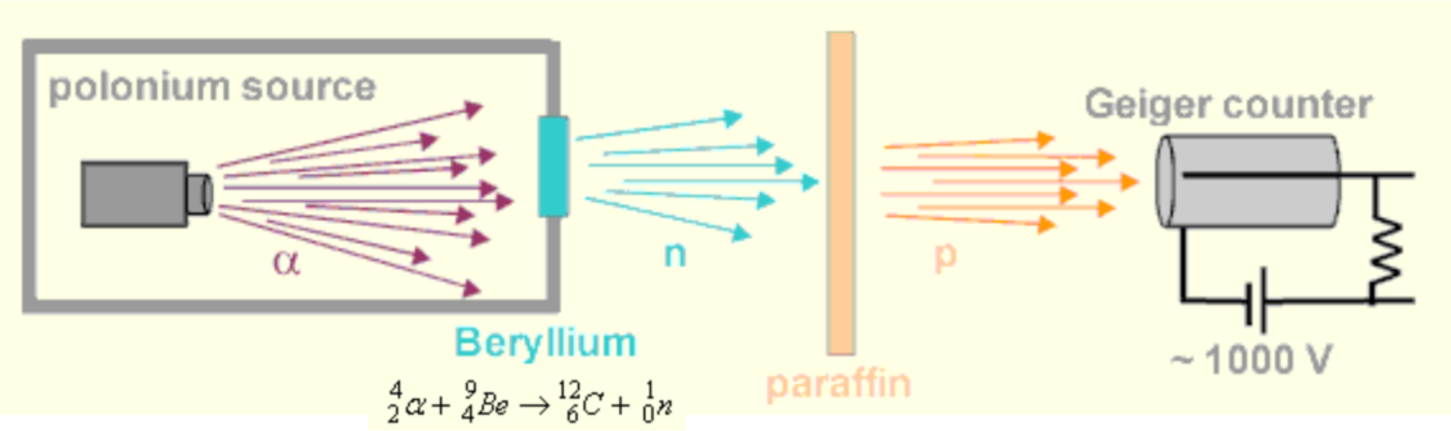
- Most alphas passed through without detection, while others were deflected at various angles and some were backscattered
- Rutherford concluded the atom had small nucleus at its center…

What about A?

- How do we reconcile A with Z?
- Hydrogen has M=1
- Masses of atoms appear to be
  - Multiples of hydrogen mass
  - About double Z
- Need more protons, but this
  - Violates known chemical properties
  - Violates charge neutrality
- Need nuclear electrons to maintain charge neutrality? (Rutherford)

Neutrons to the rescue

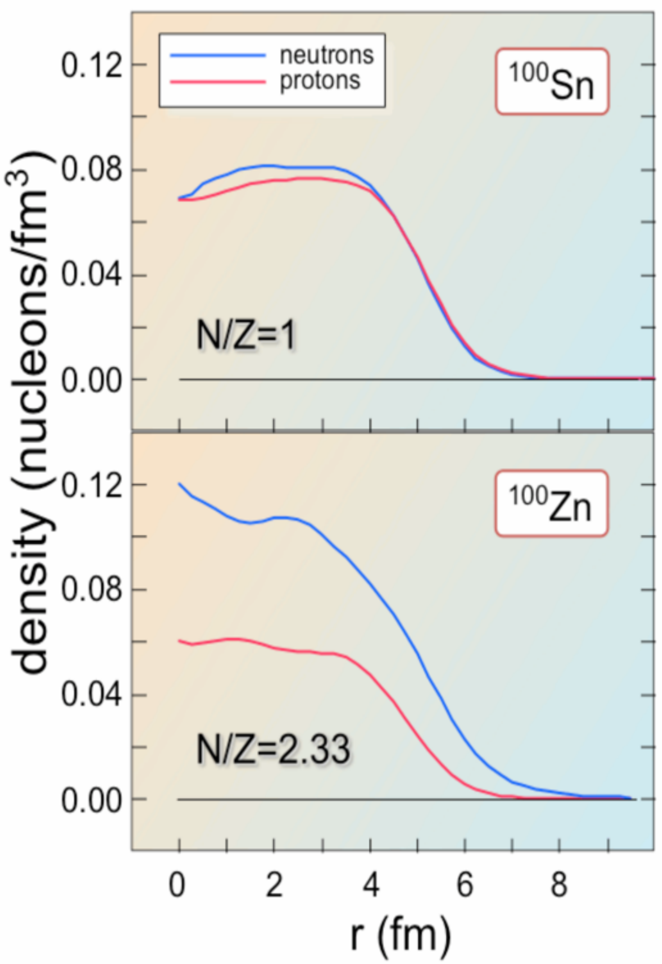
- Experiments in the 1930s
  - α on Be produced uncharged penetrating radiation not consistent with gammas because they didn't induce photoelectric effect
  - The radiation incident on paraffin produced energetic protons detected with Geiger counter
  - Chadwick showed radiation was as massive as protons, won Nobel Prize in 1935



$${}^{4}_{2}\alpha + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C + {}^{1}_{0}n$$

Nuclear size measurements

- The size of the nuclear was first measured by Rutherford (with Hans Geiger and Ernest Marsden) to be of order 10 fm
- More accurately, one can measure either a charge radius (radius of protons) or the matter radius (radius of nucleons)
  - Use leptonic probes, e.g., electron scattering, to measure charge radius (or Coulomb energy differences)
  - Use hadronic probes (made of quarks) to measure matter radius
- Some neutron rich nuclei show a difference



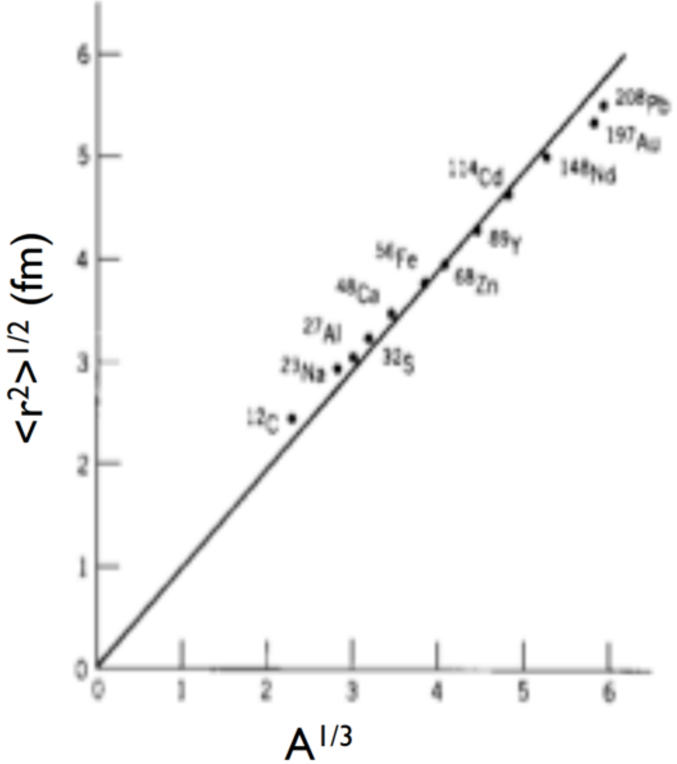
Charge radius

- The charge radius is defined as the distance at which the charge density falls to half of its value at the center
- The radius varies as the cube root of the mass

$$R = R_0 A^{\frac{1}{3}}$$

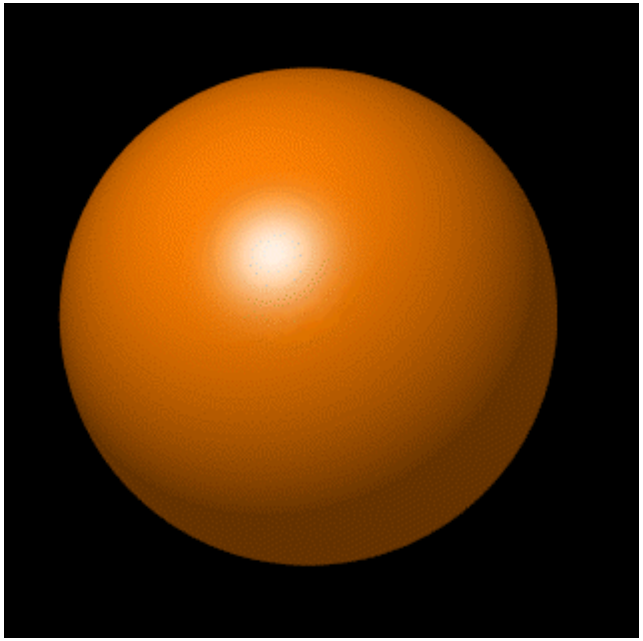
works well for most nuclei

where $R_0 = 1.2 fm$

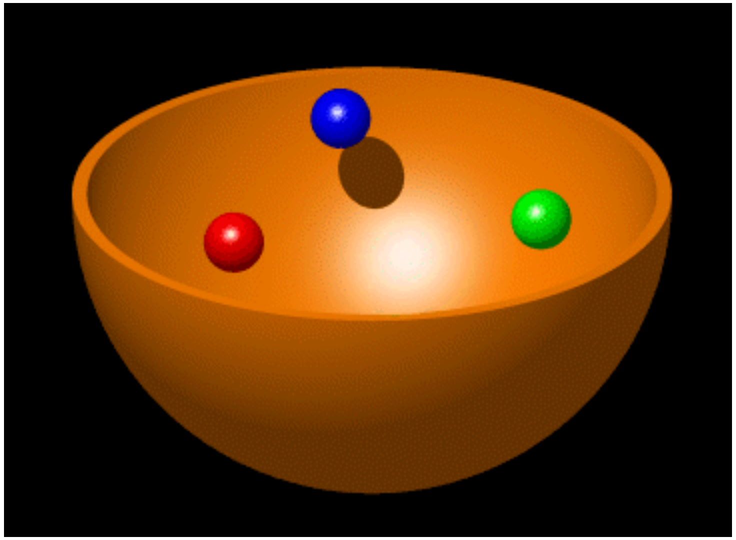


- Mean square radius of neutron is about 0.8 fm

The Standard Model



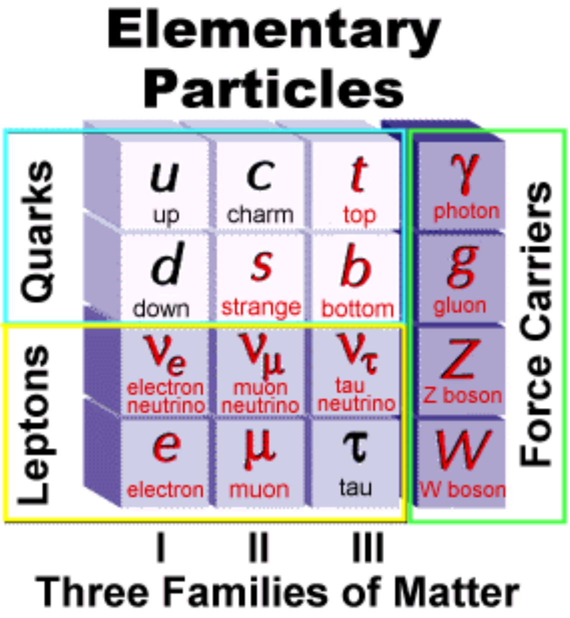
Before 1968, scientists thought that neutrons and protons were fundamental particles



Then they discovered new particles called "quarks." There are several varieties of quarks.

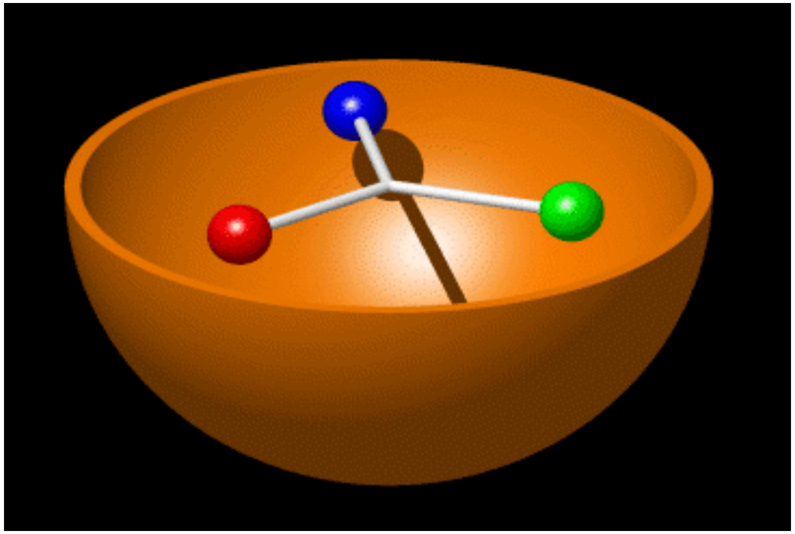
The Standard Model today

- In the modern theory, known as the Standard Model there are 12 fundamental matter particle types and their corresponding antiparticles
- Matter particles
  - Quarks and leptons
- Hadrons are made of quarks
- Force carrier particles (gauge bosons) responsible for strong, electromagnetic, and weak interactions
- Higgs boson discovered at Large Hadron Collider (2012)



Most radiation science and engineering disciplines are only concerned with the 1st family of particles (up, down, electron & positron, neutrino & anti-neutrino)

The Standard Model



Quarks are held together by other particles called gluons

Protons contain two up quarks and one down quark
+(2/3) + (2/3) – (1/3) = +1

- Protons and neutrons, both called baryons (made of 3 quarks), composed of <u>up</u> quarks and <u>down</u> quarks
  - up quark has charge of +2/3
  - down quark has charge -1/3
- The sum of the charges of quarks that make up a nuclear particle determines its electrical charge

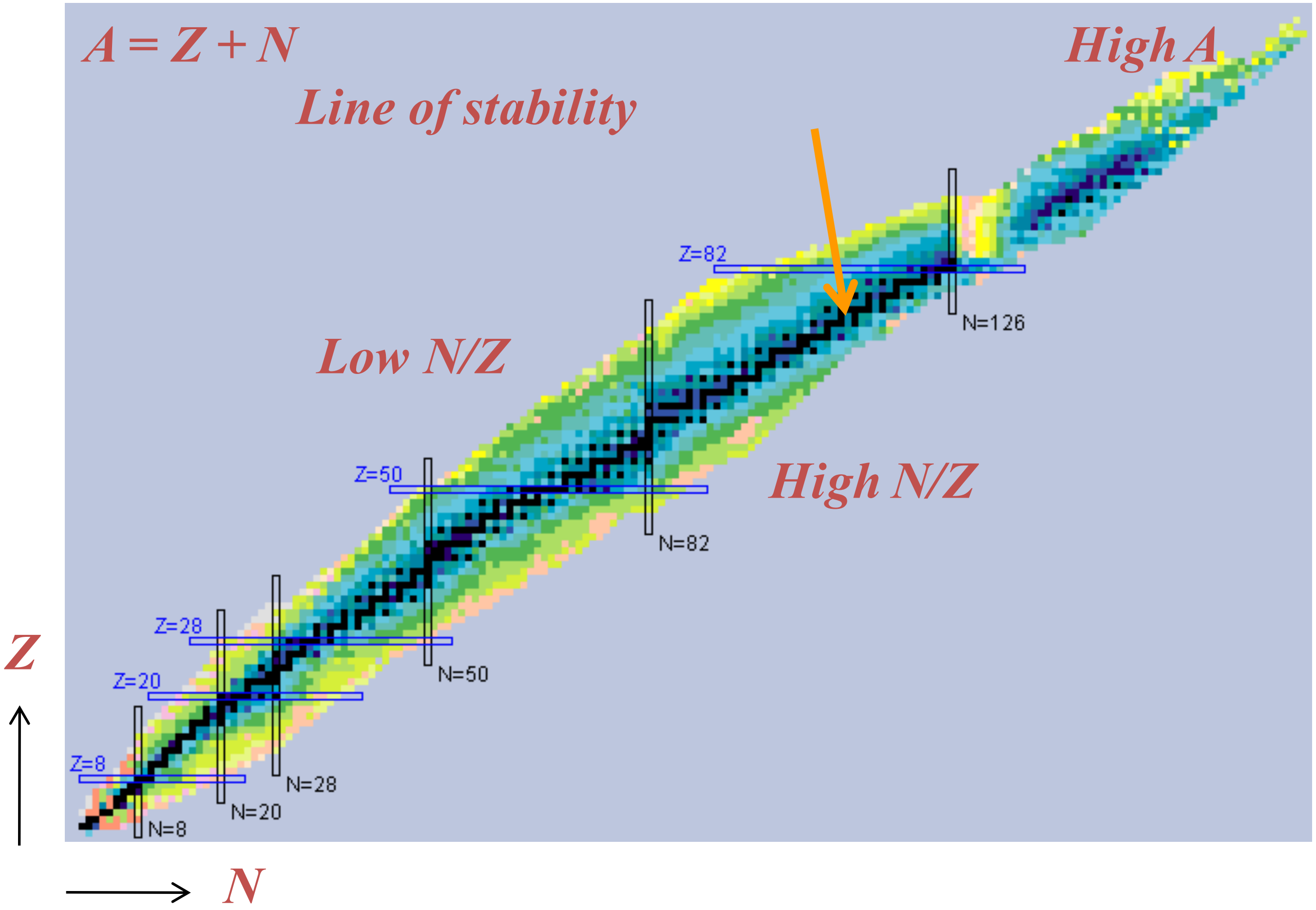
Neutrons contain one up quark and two down quarks
+(2/3) - (1/3) – (1/3) = 0

Neutron mass and the standard model today

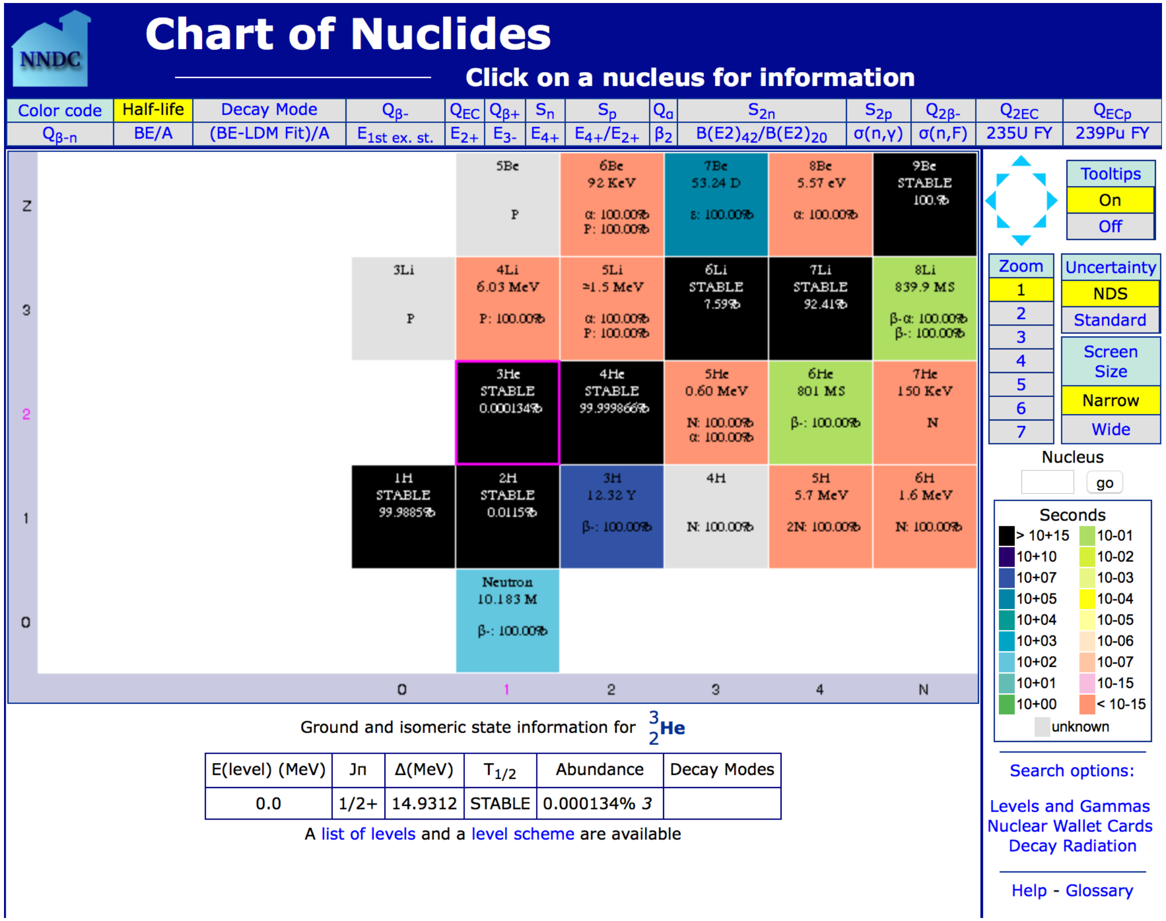
- Remember $E=mc^2$
- Very recent studies show mass of neutron 939.565 MeV/c^2 ($E=mc^2$) is much greater than the sum of its 3 quarks
- Most of the mass is thought to be due to the kinetic energy of quarks and the energies of the (massless) gluons of the strong interaction inside the neutron
- In Higgs-based theories, the property of mass is a manifestation of potential energy transferred to particles when they interact or couple with the Higgs field, which had contained that mass in a form of energy

Intro to chart of the nuclides

- A nuclide needs a proper balance of neutrons and protons to be stable
- Unstable nuclides decay toward the line of stability
- For low N/Z, a proton becomes a neutron (β^+,ε)
- For high N/Z, a neutron becomes a proton (β^-)
- For high A, the nuclide needs to lose multiple nucleons (α or SF)



Free neutrons decay



	0	1	2	3	4	N
Z		5Be P	6Be 92 KeV α: 100.00% P: 100.00%	7Be 53.24 D ε: 100.00%	8Be 5.57 eV α: 100.00%	9Be STABLE 100.%
3	3Li P	4Li 6.03 MeV P: 100.00%	5Li ≈1.5 MeV α: 100.00% P: 100.00%	6Li STABLE 7.59%	7Li STABLE 92.41%	8Li 839.9 MS β-α: 100.00% β-: 100.00%
2		3He STABLE 0.000134%	4He STABLE 99.999866%	5He 0.60 MeV N: 100.00% α: 100.00%	6He 801 MS β-: 100.00%	7He 150 KeV N
1	1H STABLE 99.9885%	2H STABLE 0.0115%	3H 12.32 Y β-: 100.00%	4H N: 100.00%	5H 5.7 MeV 2N: 100.00%	6H 1.6 MeV N: 100.00%
0		Neutron 10.183 M β-: 100.00%				

Ground and isomeric state information for $^{3}_{2}$He

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Abundance	Decay Modes
0.0	1/2+	14.9312	STABLE	0.000134% 3	

A list of levels and a level scheme are available

Search options:

Levels and Gammas
Nuclear Wallet Cards
Decay Radiation

Help - Glossary

- Becay decays mean quark transformations
- Here a down quark becomes an up quark
- Neutron: 1 up, 2 down
- Protons: 2 up, 1 down

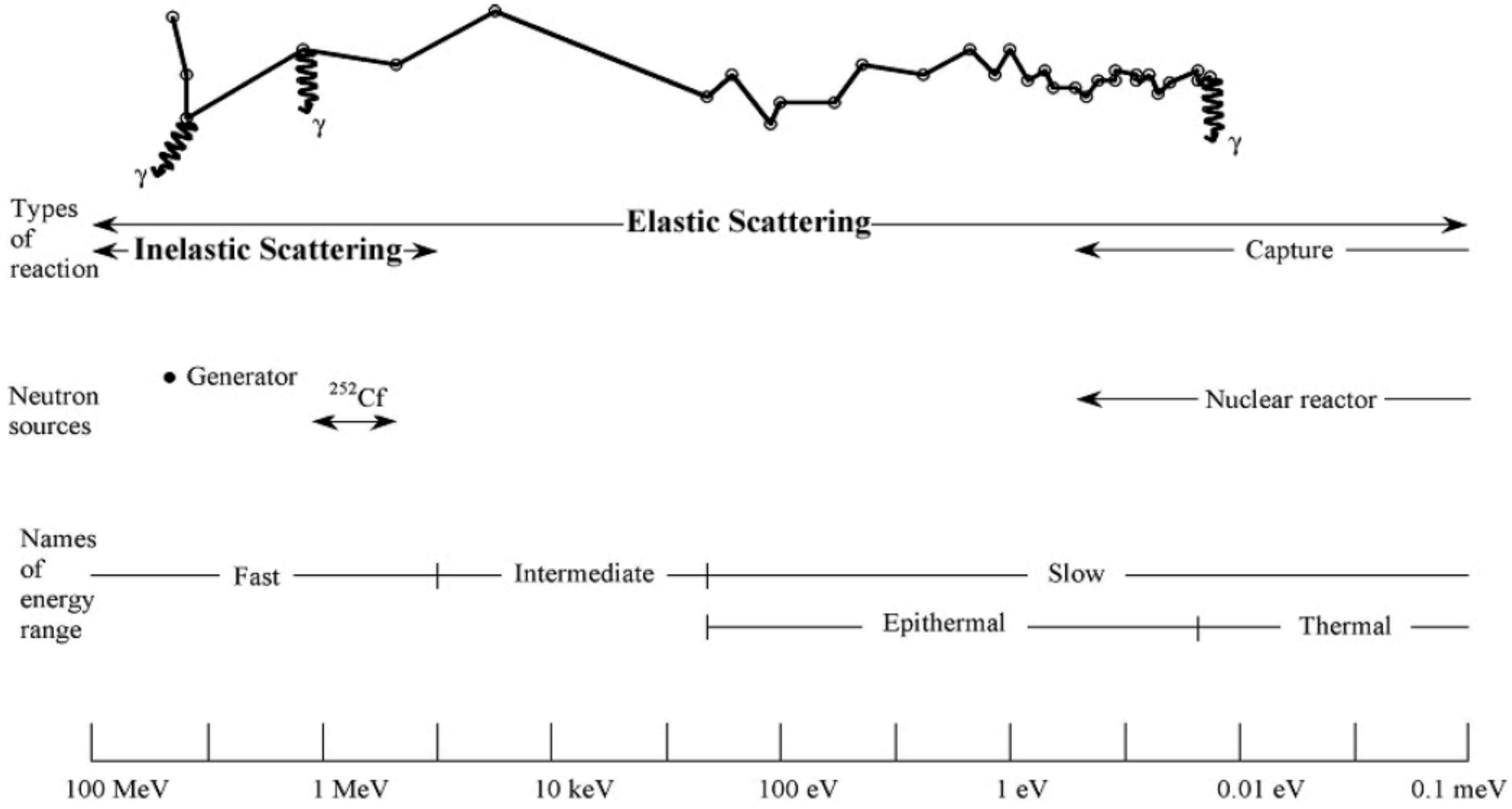
Neutron Interactions

Radiation categories

Charged particulate radiations	Uncharged radiations
Heavy charged particles ~ 10^{-5} m	Neutrons ~ 10^{-1} m
Fast electrons ~ 10^{-3} m	X-rays and gamma rays ~ 10^{-1} m

- Charged particulate radiations continuously interact through the coulomb force with the electrons present in the medium through which they pass
- Uncharged radiations can undergo catastropic interactions that radically alter the properties of the incident radiation in a single encounter, or they can pass through a material without interaction

Neutron interactions with matter

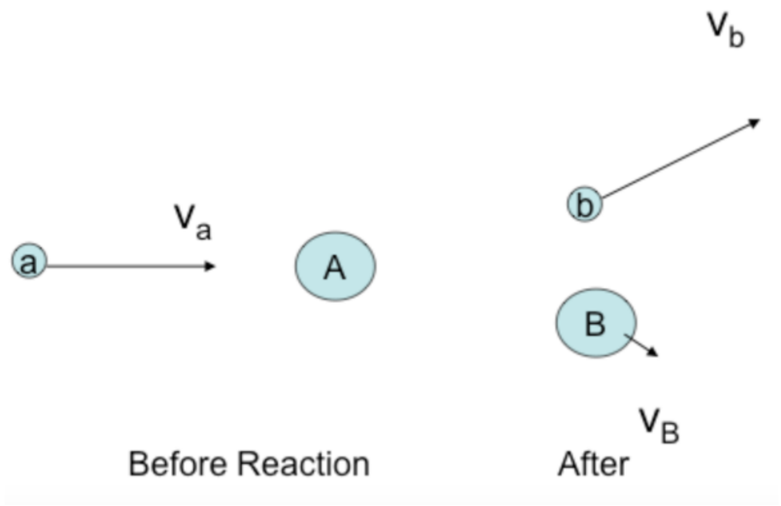


Neutron energy notes

- Fission neutron energies are characterized Maxwell-Boltzmann or a Watt spectrum
- ^{113}Cd has a strong energy cutoff below ~0.5 eV
- Thermal neutrons are in equilibrium with surrounding medium; most probable energy at 20°C for Maxwellian distribution if 0.025 eV (~2 km/s)
- Cold neutrons (<0.025 eV) are in thermal equilibrium with very cold surroundings such as liquid deuterium, used for neutron scattering experiments

Basics about reactions

- Nomenclature A(a,b)B
  - A is the target, usually at rest
  - a is the incident projectile (often referred to as the beam) which has incident kinetic energy T_a
  - b is an outgoing particle which has kinetic energy T_b
  - B is the residual nucleus (usually somewhat similar to A)



Two distinct types of reactions

- Direct reactions
  - Proceed rapidly, time scale equivalent to the time taken for the incident particle to cross the diameter of the nucleus
  - No formation of a compound nucleus
- Compound nucleus
  - A compound nucleus is formed and left in an excited state
  - All nucleons share in the excitation
  - Excitation is lost through the emission of particles and gamma rays through competing decay processes

Examples of direct reactions

- Elastic scattering, a=b, A=B
- Inelastic scattering, a=b, B=A* (excited state of A)
- Transfer reactions, one or two nucleons transferred between projectile and target
- Knockout reactions (high energy reactions to remove one or more nucleons, e.g., caused by charged particle beam)

Reaction examples

- (n,xn) – multiple neutrons out (transfer)
- (n, c.p.) – “particle ejection” of short range heavy particle, e.g., α or p, sometimes with gammas (transfer)
- (n,γ) – ”Capture” neutron in, compound nucleus formed, gamma out
- (n, f) – compound nucleus formed, energetic fission fragments + neutrons + gammas out

Conversed properties in low-energy nuclear reactions

- Number of nucleons
- Total energy
- Linear momentum
- Angular momentum

Q value for nuclear reactions

- The Q value is the total energy converted from mass energy to kinetic energy (*T*)

$$Q = -\Delta M c^2 = \left(M_A + M_a - M_B - M_b\right)c^2$$

$$Q = \Delta T = T_B + T_b - T_A - T_a$$

- If the Q value is positive, exothermic reaction
- If Q is negative, endothermic reaction
- For exothermic reaction, mass energy is converted to kinetic energy
- For endothermic reaction, kinetic energy is converted to mass energy
- Elastic scattering is neither exo- nor endothermic

Reaction cross sections

- If you bombard a target of ^{232}Th with protons, one could have a number of different reactions, e.g.,
  - Proton is absorbed and neutron is emitted
  - Proton is absorbed and the compound nuclear fissions
  - Proton is absorbed and an alpha particle is emitted
- Reaction cross sections measure the probability that any of these particular reactions, related to a particular final state, will occur
- The sum of all cross sections that remove protons from the beam would be the total absorption cross section for protons at that bombarding energy
- Cross sections depend on nuclear structure properties
- Unit: barn = 10^{-28}m^2 = 100 fm^2

Reaction cross sections

- The reaction rate is given by $R = It\sigma$, where I is the intensity of the beam in particles/s, t is the thickness of the target in atoms/cm^2, and σ is the cross section in units of cm^2
- Differential cross section is given by

$$\frac{d\sigma}{d\Omega}$$

- Reaction rate for which the outgoing particles will go into the solid angle dΩ is given by

$$dR = It\left(\frac{d\sigma}{d\Omega}\right)d\Omega$$

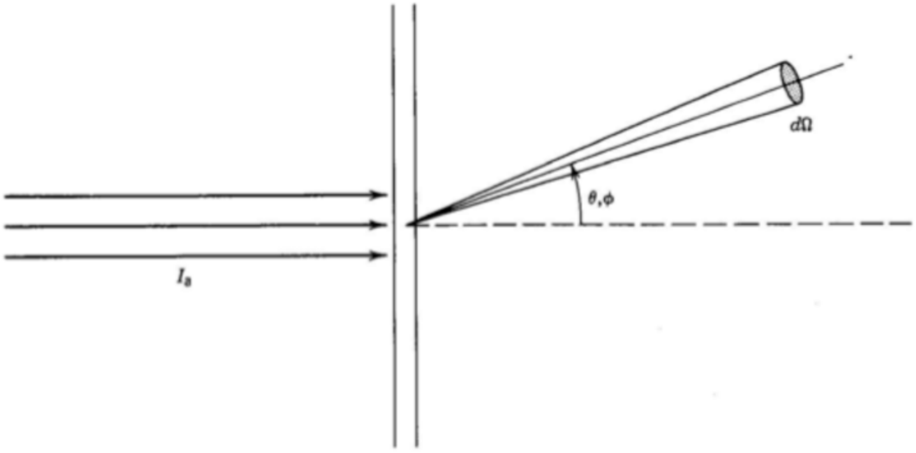
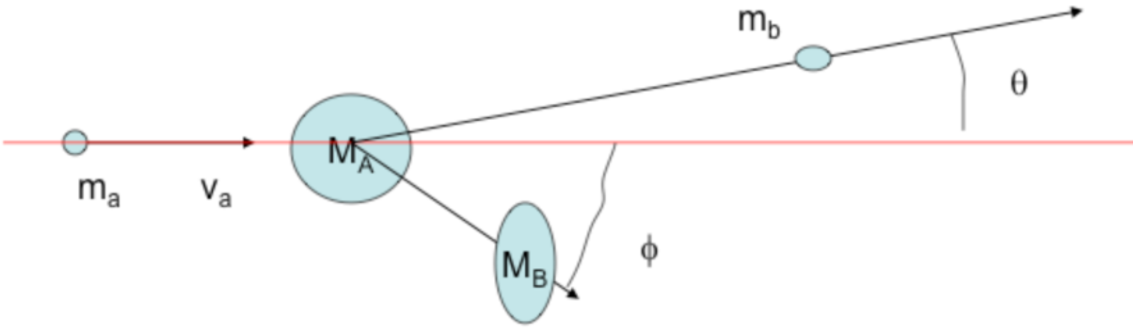


Figure 11.6 Reaction geometry showing incident beam, target, and outgoing beam going into solid angle $d\Omega$ at θ, ϕ.

Finding cross sections and unknowns from a direct reaction



$$m_a v_a = m_b v_b \cos\theta + m_B v_B \cos\phi$$

$$m_B v_B \cos\phi = m_a v_a - m_b v_b \cos\theta$$

$$m_B v_B \sin\phi = m_b v_b \sin\theta$$

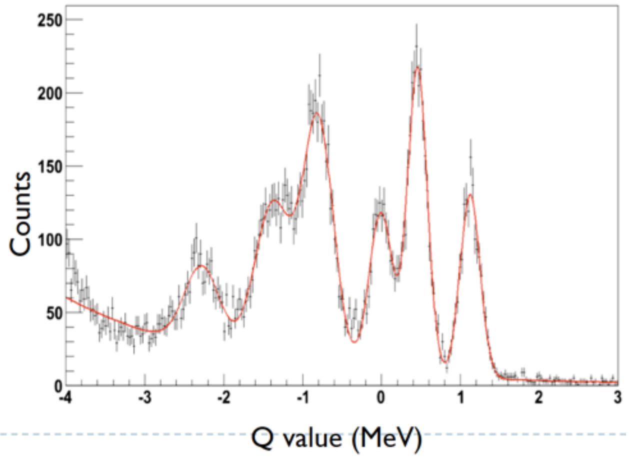
Known/observed:

- Beam energy
- Angles
- Masses of A, a, and b (not B)
- Kinetic energies of a and b

Finding cross sections and unknowns from a direct reaction

- The number of reactions observed gives cross sections
- Q value is determined on an event-by-event basis from the known/observed quantities as

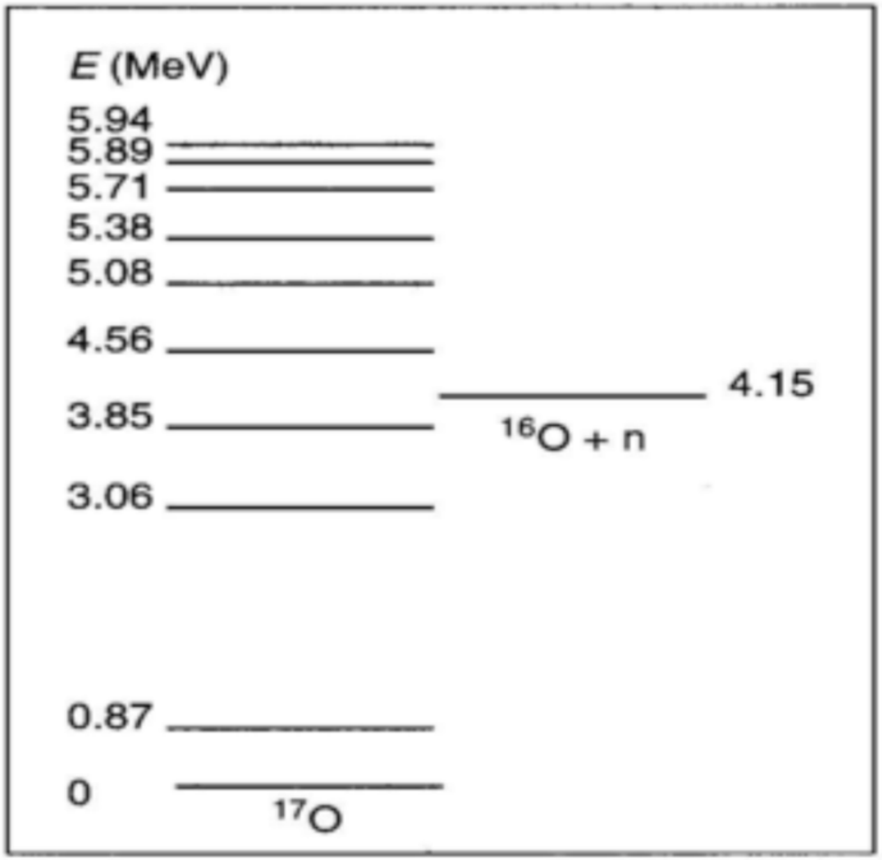
$$Q = T_b\left(1+\frac{m_b}{m_B}\right) - T_a\left(1-\frac{m_a}{m_B}\right) - 2\sqrt{\frac{m_a}{m_B}\frac{m_b}{m_B}T_aT_b}\cos\theta$$



- Difference in Q-value for different peaks in the spectrum will give the energies of excited levels, $E_x = Q_{gs} - Q$
- The Q-value for population of the ground state can be used to find $m_B = m_A + m_a - m_b - Q/c^2$

Example transfer reaction: $^{16}O(d,p)$

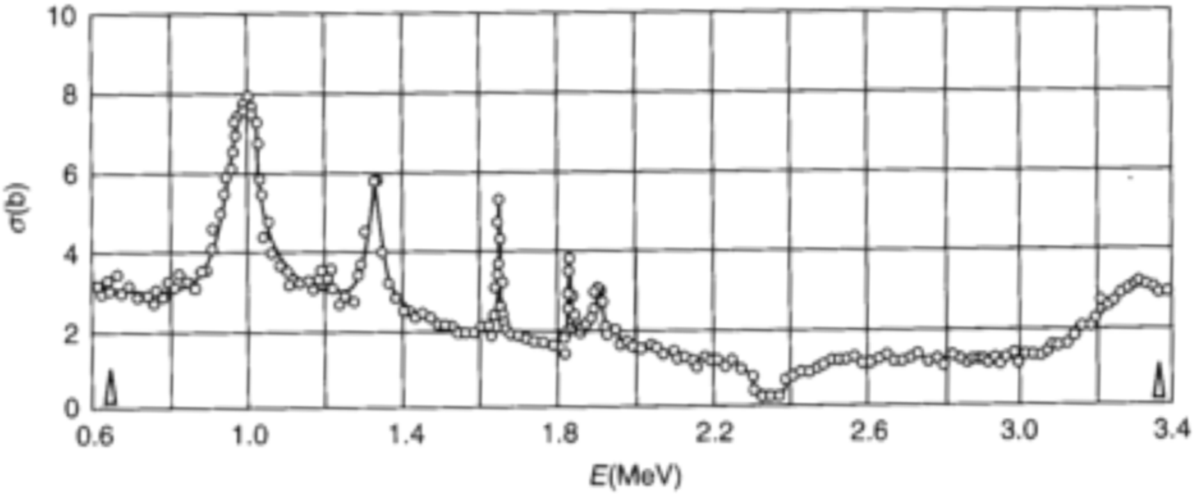
- The populated states of ^{17}O (same as ^{16}O plus neutron) are shown in the level scheme
- Also shown is the energy level of ^{16}O + a free neutron, indicating that the four lowest energy states are bound against neutron emission
- The higher-lying states live for a short time before decaying and have a width in energy related to their lifetime
- These unbound states are called **resonances** of the ^{16}O plus neutron system



^{16}O neutron cross section

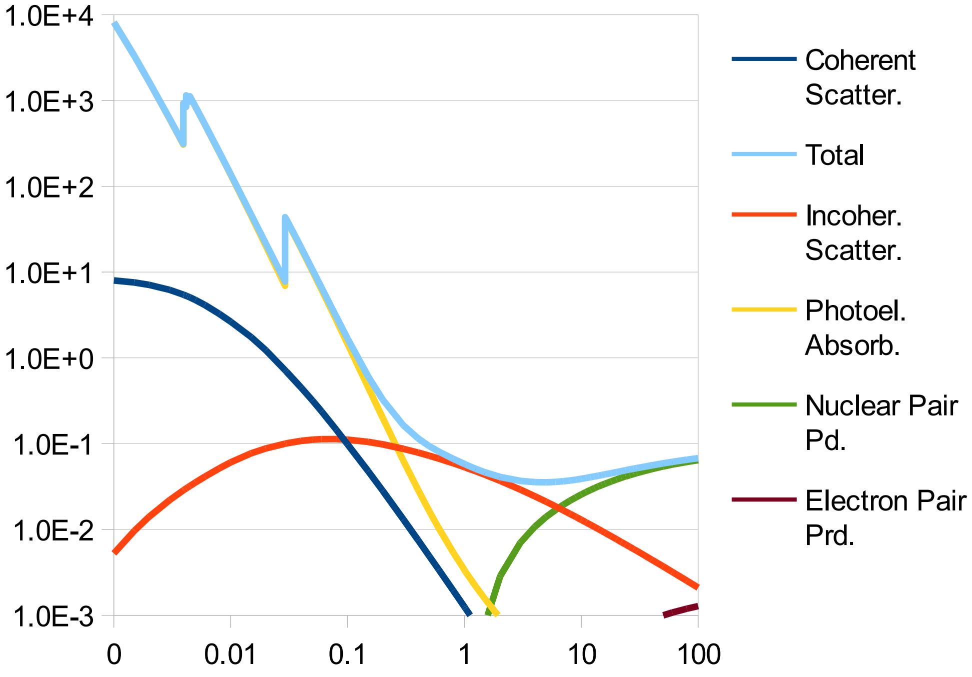
- If the low energy neutrons are incident on ^{16}O at a resonance energy, the cross section is much larger

Figure 11.6 | Total Neutron Cross Section for ^{16}O as a Function of Center of Mass Energy



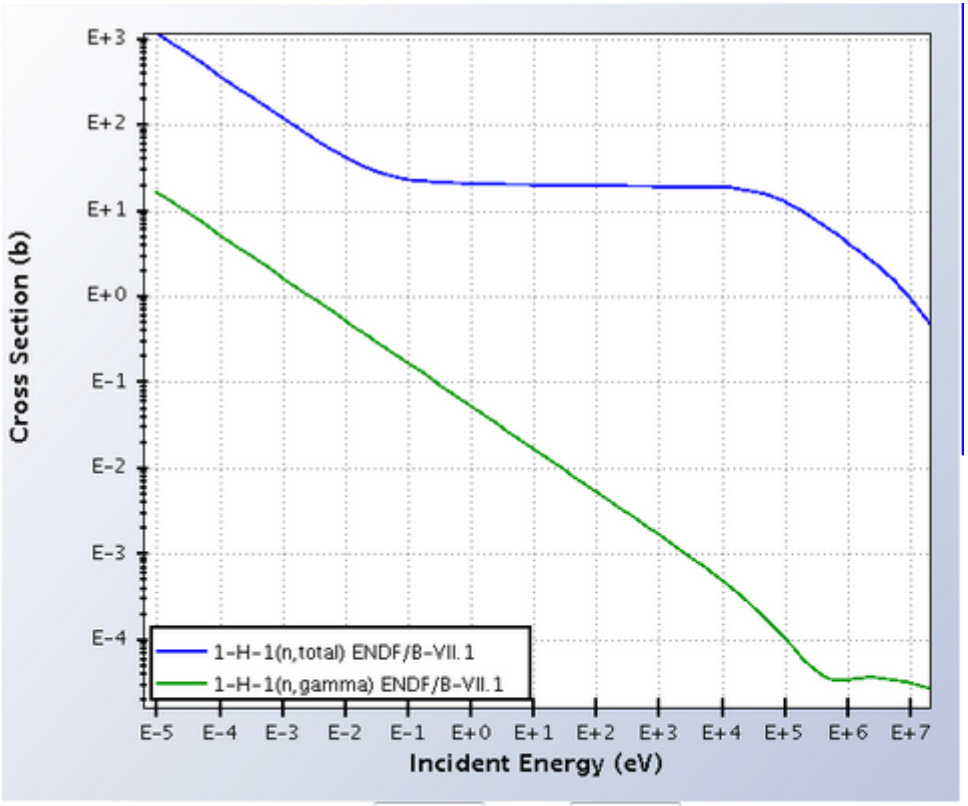
From D. J. Hughes and R. B. Schwartz, *Neutron Cross Sections*, second edition. Upton, NY: Brookhaven National Laboratory, 1958. Courtesy of Brookhaven National Laboratory.

Shapes of neutron cross sections



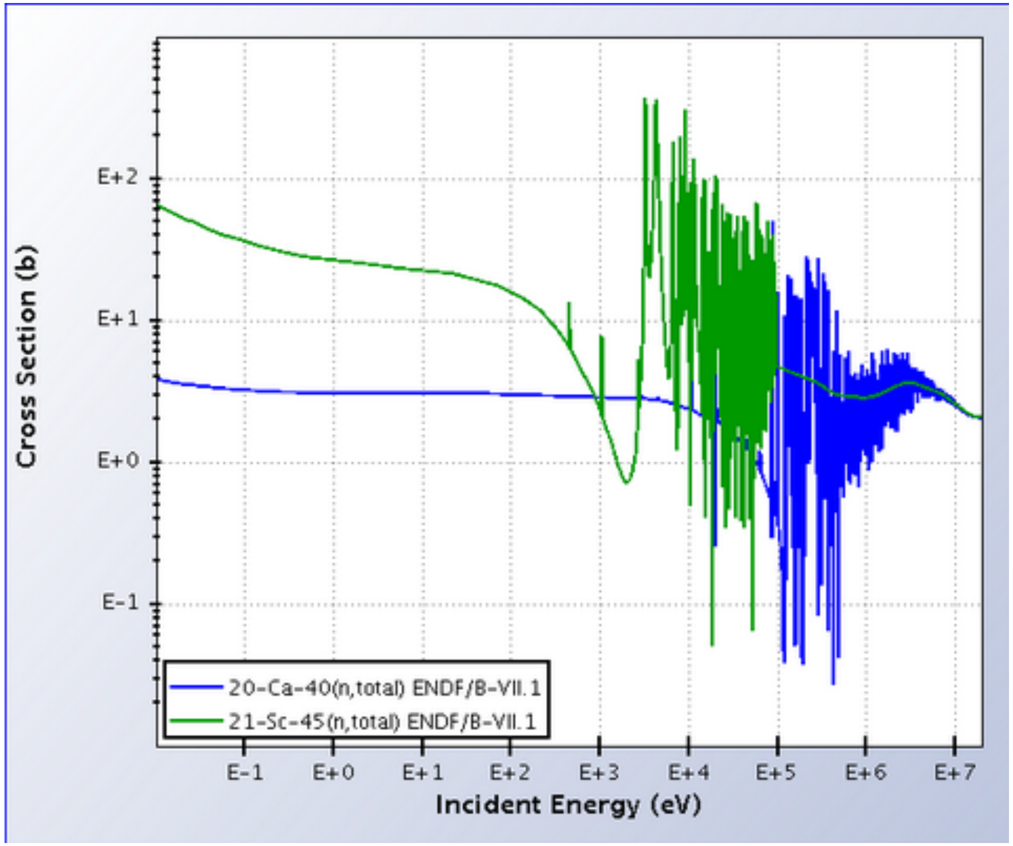
- Neutron cross sections NOT as “clean” as electromagnetic cross sections (shown here)
  - Mostly smooth
  - “Simple” relation between σ and E
  - γ cross section entirely calculable

Shapes of neutron cross sections



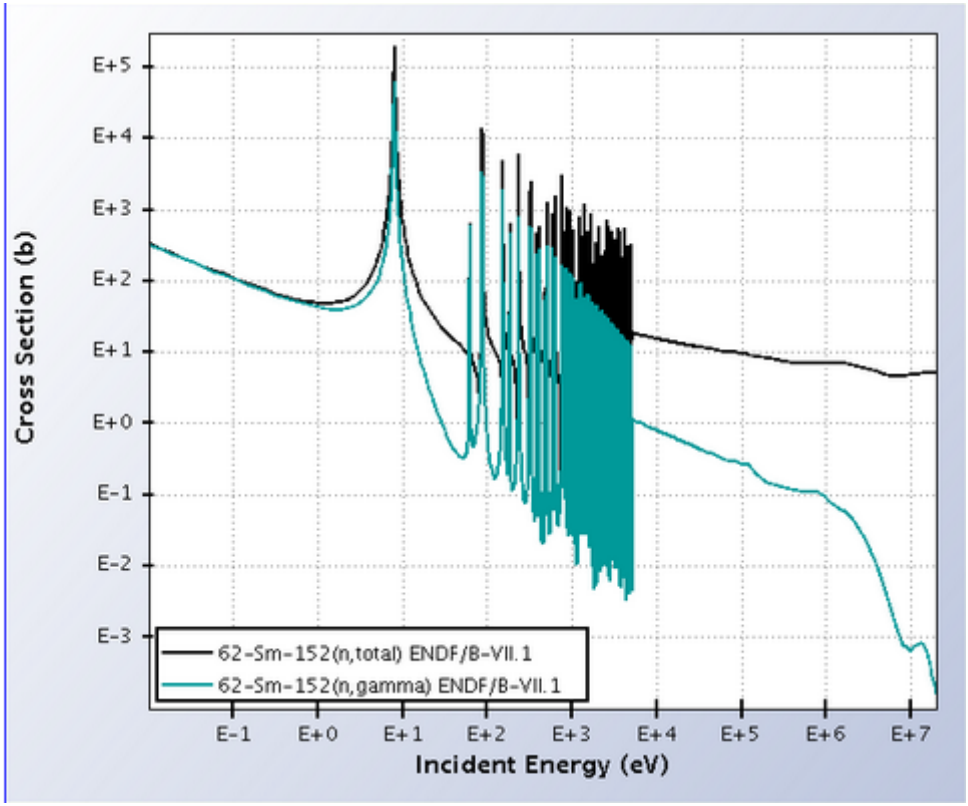
- ^{1}H cross sections shown
- 1/v behavior at very low energy
- Nuclear force between target nucleus and neutron has longer time to interact at lower speed
- Capture is not a major contributor for ^{1}H

Shapes of neutron cross sections



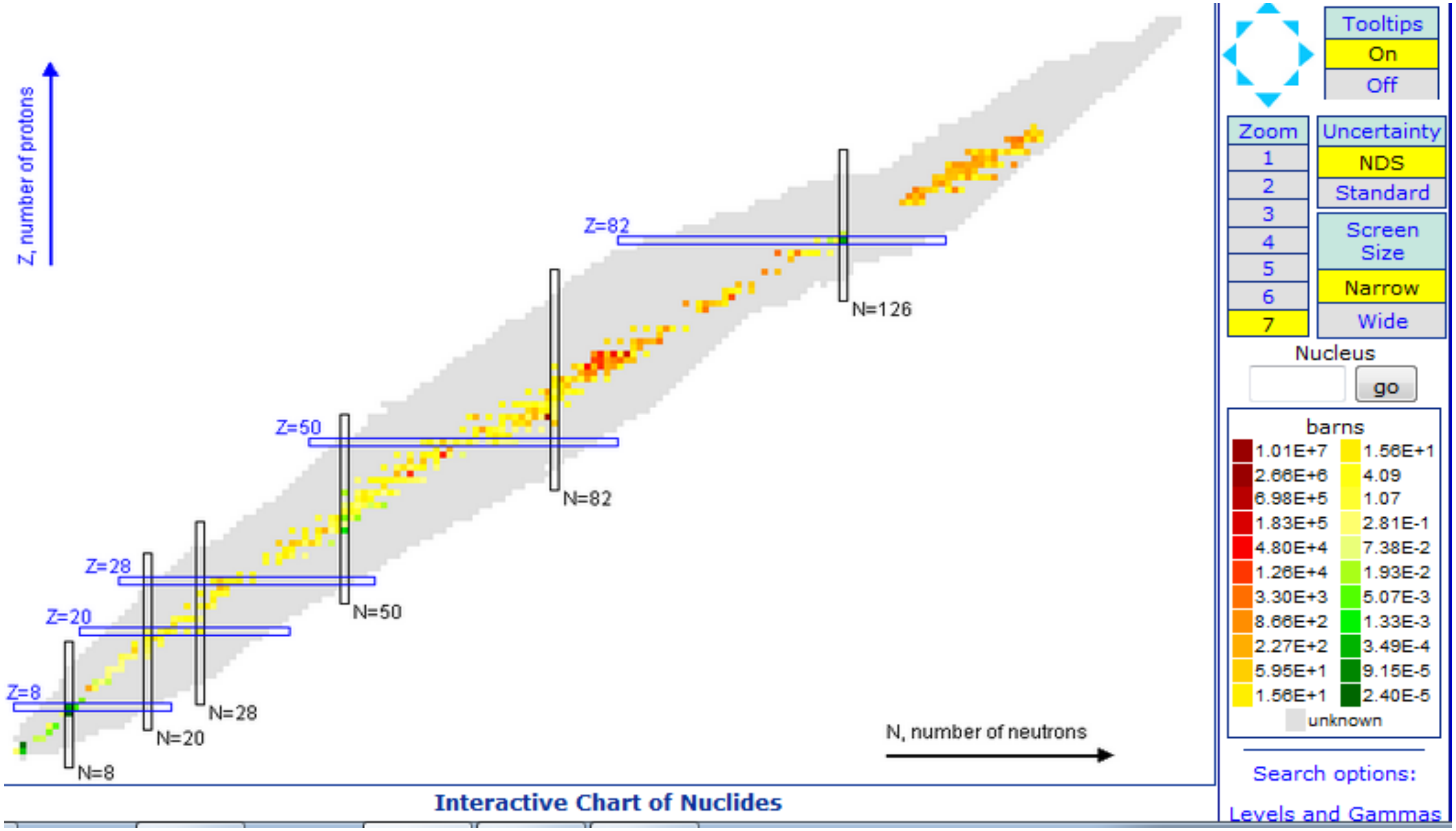
- Examples for some higher mass nuclei shown
- More nucleons, more structure
- 1/v behavior still present at low energy
- Resonances are now evident

Shapes of neutron cross sections



- More nucleons, more structure
- 1/v behavior, resonances still present
- Capture now plays very important role

Thermal neutron capture cross section map



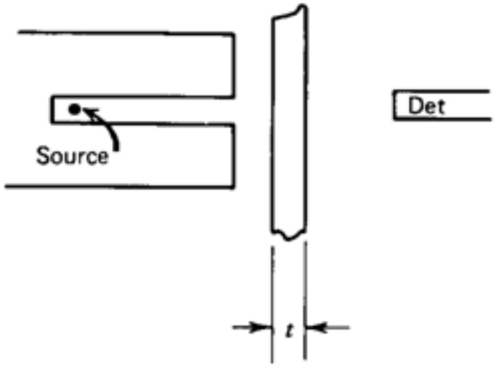
Macroscopic cross section

- Macroscopic cross section for single isotope

$$\Sigma = \frac{\rho \sigma N_A}{W} = N\sigma$$

- Mean free path = $1/\Sigma$
- In a neutron detector, these quantities determine the probability of interaction (of some type) per unit distance (e.g., cm) of travel, or the mean distance (e.g., in cm) until an interaction occurs

Neutron attenuation



$$\frac{I}{I_0} = e^{-\Sigma_{\text{tot}}\, t}$$

$$\Sigma_{\text{tot}} = \Sigma_{\text{scatter}} + \Sigma_{\text{rad. capture}} + \ldots$$

$$\Sigma = N\sigma$$

Neutron speed and wavelength

- Speed of a non-relativistic neutron (< 20 MeV)

$$v = \sqrt{2E(MeV)/m_n}=1.38\ cm/ns\sqrt{E(MeV)}$$

- Wavelength of a non-relativistic neutron

$$\lambda = \frac{2\pi\hbar}{\sqrt{2mE}} = \frac{2\pi\hbar c}{\sqrt{1880E}} = \frac{28.55\ fm}{\sqrt{E(MeV)}}$$

Neutrons in condensed matter research

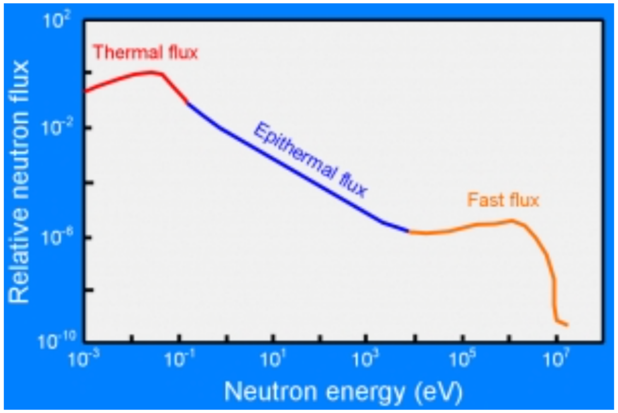
- Any (currently) practical neutron source makes fast neutrons
- Not useful for condensed matter research
    - Molecular energies are around 100 meV
    - Interatomic spacings are around 1 Å
- 1 Å ~ 81.8 meV ~ 3956 m/s
- Cold and thermal neutrons can be used in neutron diffraction experiments to determine material properties

Fast neutron moderation

- Moderation (elastic collisions)

$$E_{\max} = \frac{4E\cdot\ A}{(A+1)^2} \quad \text{(derived later)}$$

$$\overline{E} = \frac{2E\cdot\ A}{(A+1)^2}$$



- Number of collisions need to bring E_0 to E_n (2 MeV to 0.025 eV)

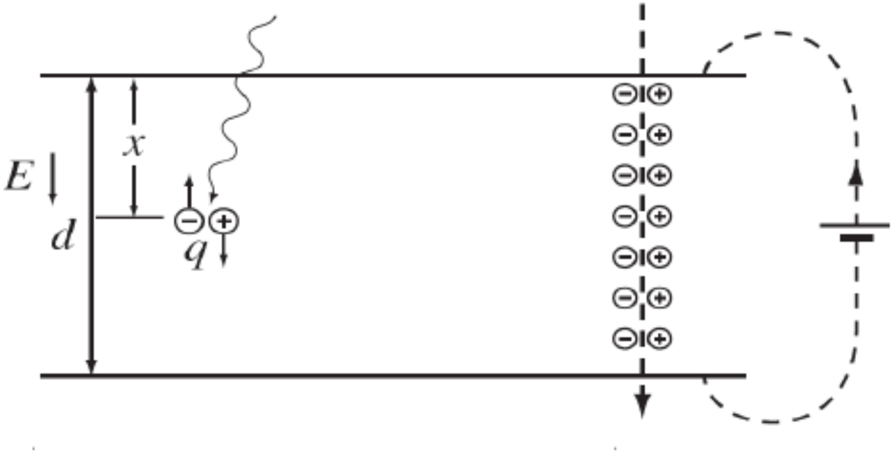
$$n = \frac{\ln \dfrac{E_n}{E_0}}{\ln \dfrac{(A^2+1)}{(A+1)^2}}$$

H	27
D	31
He	48
Be	92
C	119
U	2175

Detection basics

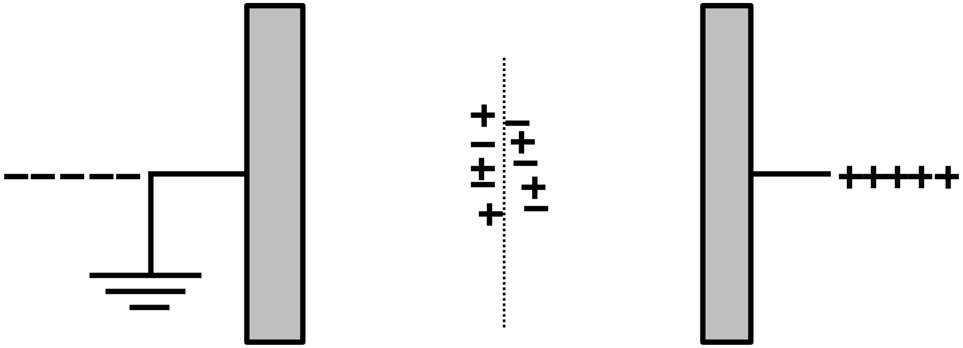
What is a radiation detector?

- Radiation (uncharged / charged) interacts in a gas, liquid, or semiconductor material, producing charge
- Collection of charge produced may be direct or indirect
- If direct, charge carriers are formed and swept to collecting electrodes by an applied electric field *E*
- The movement and collection of charge is sensed in electronic readout system



Charge induction in the case of direct charge collection

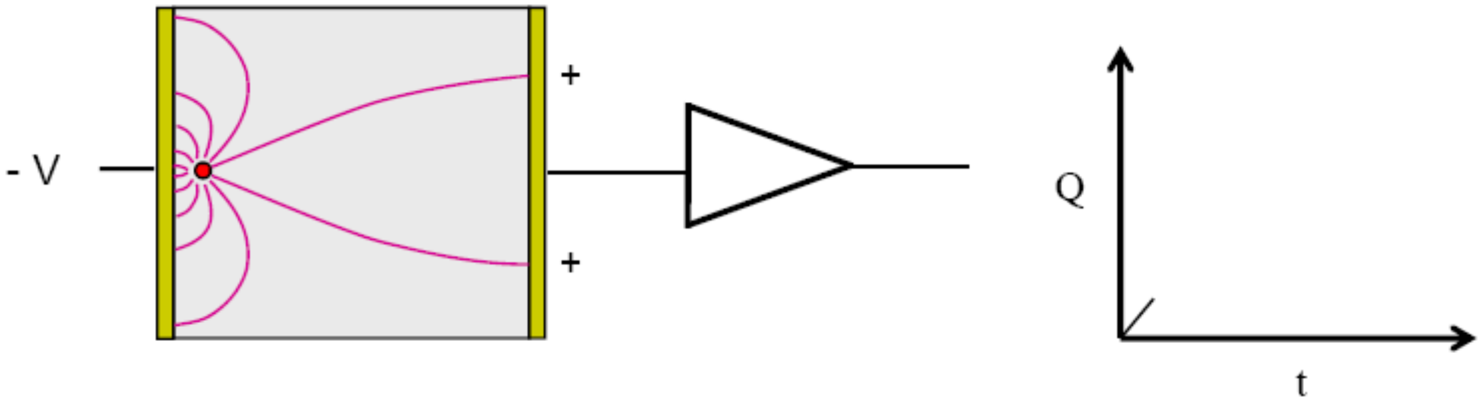
- Moving charges cause mirror charges to form in nearby conductors



- This mirror charge motion is what is actually sensed in the electronics connected to the detector
- This is the basis of the Shockley-Ramo Theorem
- Actually, both moving positive and negative charge clouds cause mirror charge at each electrode

Charge induction

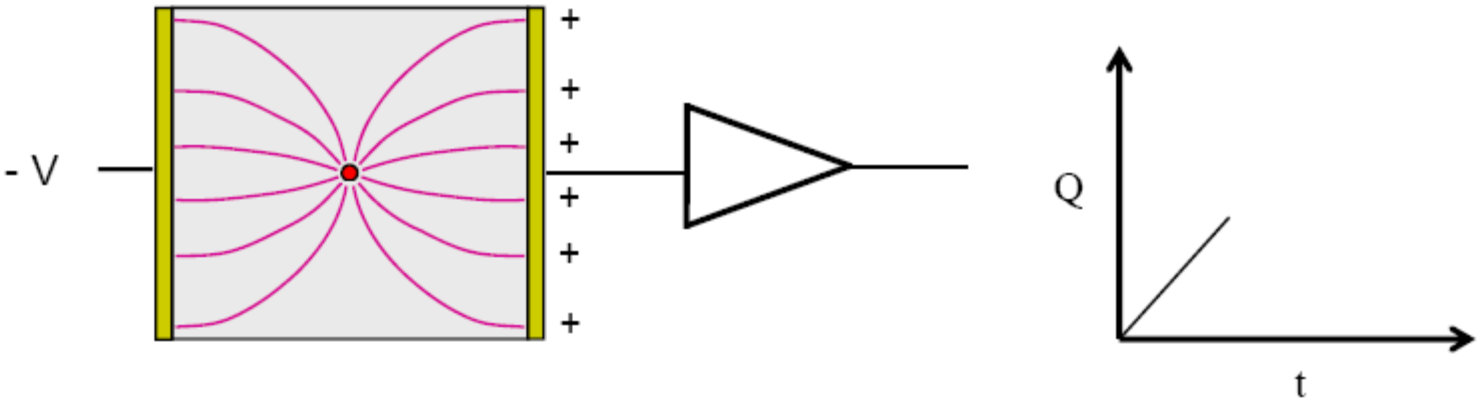
- The charge liberated by interaction of radiation (e.g., a neutron) in the detector results in an electric field that emanates in all directions and influences the electrode conductors



- The electrodes are held at a constant voltage, and thus the electrons on the surface of the conductor will redistribute due to the forces produced from the spatially varying electric field

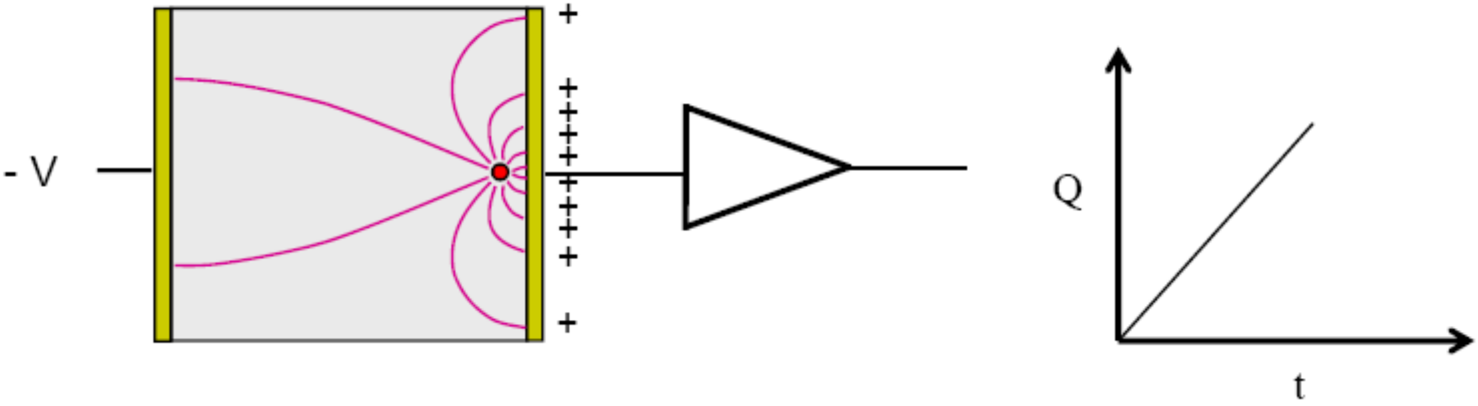
Charge induction

- The redistribution of electrons and holes (or + ions) forms mirror charge that is characteristic of the location and amount of space charge generated by the radiation interaction



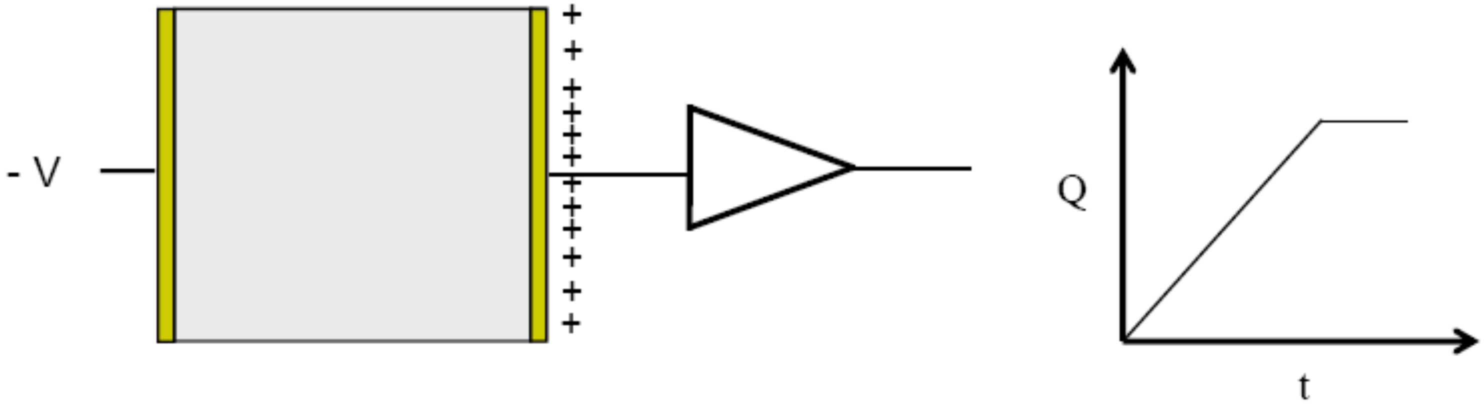
Charge induction

- As the carriers drift from the initial interaction site, the mirror charge on an electrode will respond corresponding to the changing electric forces



Charge induction

- The result of this process is a current induced within the electrode circuit due to the capacitive coupling of the electric field generated by the transporting charges

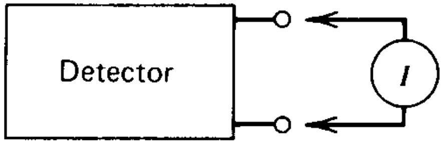


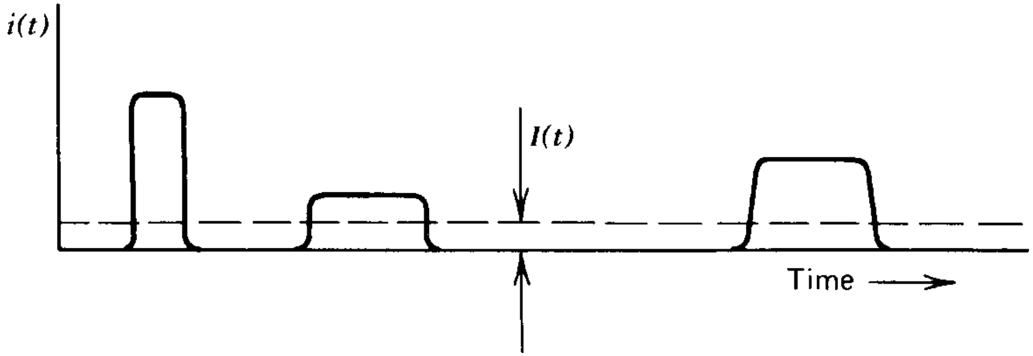
- The time that it takes for all charge to be "collected" to the electrodes is t_c, and the total charge induced at t_c is Q_s

Modes of detector operation

- If charge produced by radiation interaction is not directly collected, the indirect signal (e.g., light) needs to be converted back to charge (e.g., scintillators)
- Radiation detectors can be operated in one of two modes
  - Pulse mode, where they are sensitive to individual quanta of radiation, or
  - Current mode, where a time average of individual current bursts is recorded
- Only in pulse mode can a radiation detector perform tasks of radiation counting and spectroscopy

Current mode

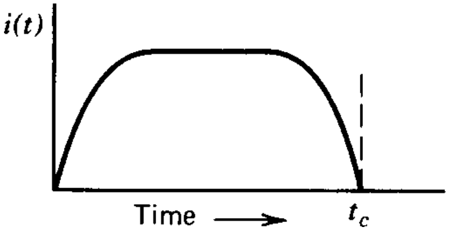




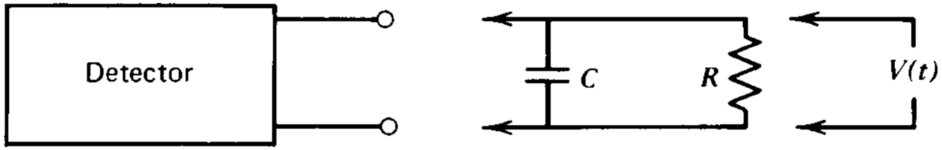
$$I(t) = \frac{1}{T}\int_{t-T}^{t} i(t')\,dt'$$

- Assume measuring device has fixed time response *T*
- Average current depends on interaction rate of individual quanta and charge per interaction
- Record *I(t)*, the time average of individual current bursts

Pulse mode



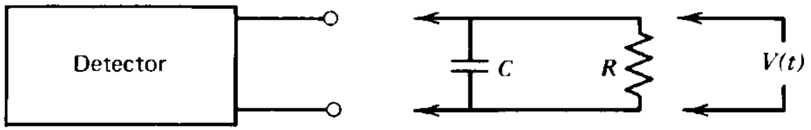
Each quantum of radiation gives rise to a voltage pulse

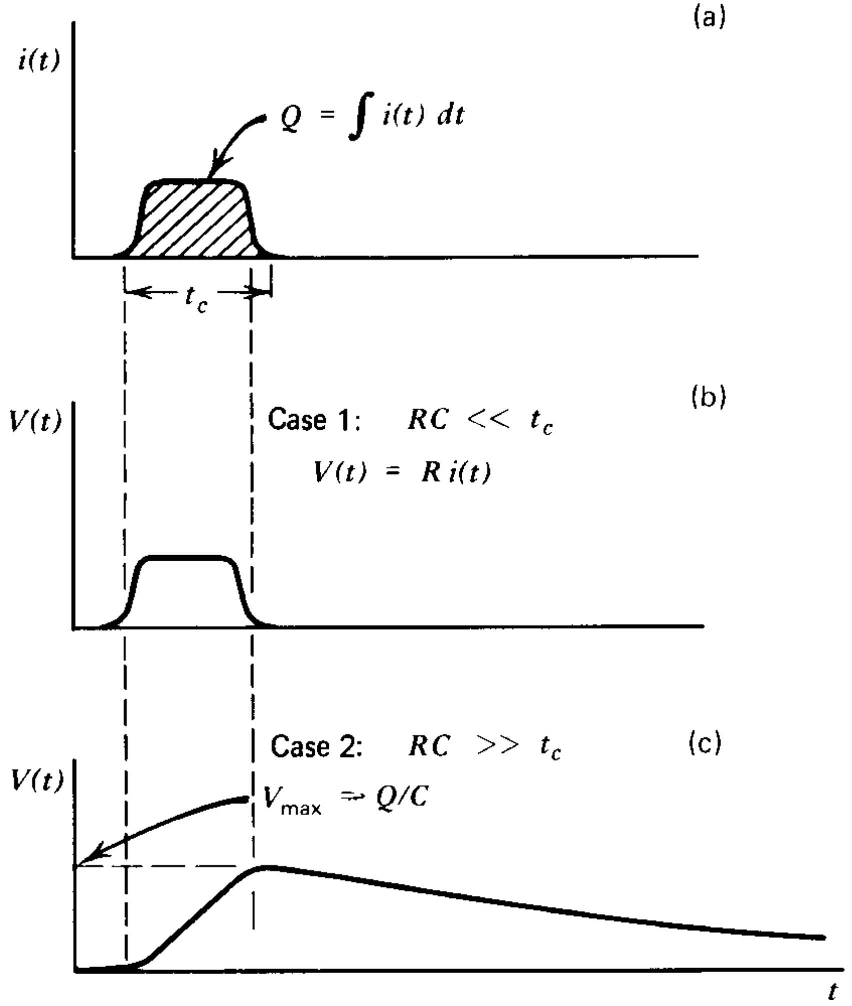


V(t) is dependent upon the input resistance of the circuit R and C represents the capacitance of both the detector itself and the measuring circuit

Impact of RC

- Small *RC* can be better for high event rates when timing information is more important than energy information
- For large RC, detector current is first integrated on the capacitor ($Q = CV$)
- Subsequently, it is discharged through the resistance





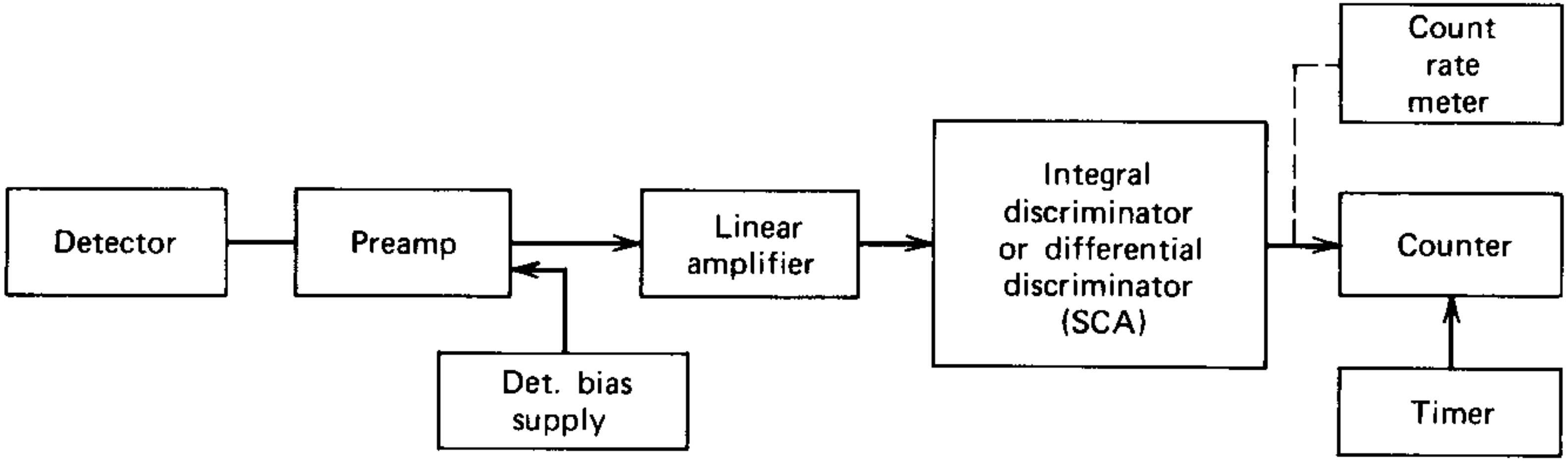
Pulse processing

- Pulse processing allows for
  - counting of radiation interactions
  - the extraction of energy, timing, and/or shape information from the signals produced by radiation interactions
- Pulse processing electronics are either analog or digital in nature
- Often times, both analog and digital electronics are used in a pulse processing system
- Linear pulses carry information in their amplitude and sometimes in their shape
- Logic pulses carry information by their presence or absence, or by the precise time of their appearance

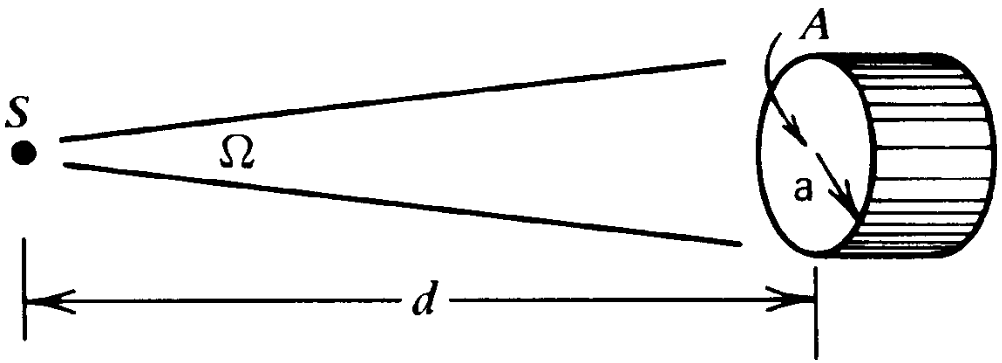
Processing of radiation pulses

- Two common pulse processing tasks are radiation counting or radiation spectroscopy
- Different pulse processing circuits are required for each task
- For neutron spectroscopy, a deconvolution/unfolding process is also required (beyond the scope)
- In radiation counting, individual radiation quanta are counted, e.g., number of gamma ray interactions or number of neutron interactions
- One metric used to compare one counting detector to another is detection efficiency

Signal chain for pulse counting



Detection efficiency



Absolute efficiency

$$\varepsilon_{\text{abs}} = \frac{\text{number of pulses recorded}}{\text{number of radiation quanta emitted by source}}$$

Intrinsic efficiency

$$\varepsilon_{\text{int}} = \frac{\text{number of pulses recorded}}{\text{number of radiation quanta incident on detector}}$$

Other performance metrics for detectors and systems

- Energy resolution – deals with ability to resolve spectral features
- Dead time and pile-up insensitivity
- Timing resolution, individual detector or system-level
- Detection metrics include minimum detectable activity and receiver operator characteristic (ROC) curve performance, which takes both sensitivity and specificity into account
- Position resolution
- Angular resolution
- There are also *many* metrics to evaluate imaging performance including signal-to-noise ratio, contrast-to-noise ratio, and the modulation transfer function
- Some of these should be addressed later in this course

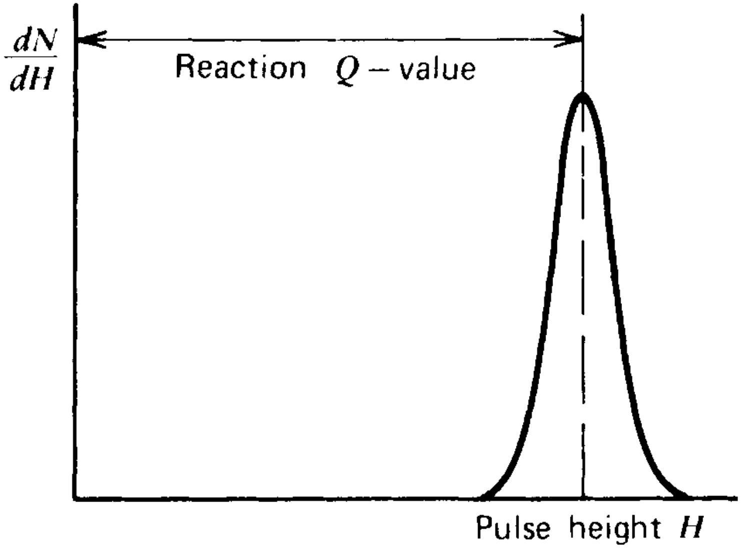
Slow neutron detection

Slow neutron detection basics

$$\text{target nucleus} + \text{neutron} \rightarrow \left\{ \begin{array}{l} \text{recoil nucleus} \\ \text{proton} \\ \text{alpha particle} \\ \text{fission fragments} \end{array} \right.$$

- Q-value is energy of reaction products originating from difference in mass before and after reaction
- For slow neutron detection, need exoenergetic (positive Q) reactions to provide energetic reaction products
- If all of this energy is deposited in a detector (assume large detector)…..

Detector response



- Full energy peak response
- Not typical of gaseous detectors, where charged particle range may be ~ detector size
- Measured energy not indicative of incident neutron energy

Reactions in slow neutron detection

$${}^{10}_{5}B(n,\alpha)^{7}_{3}Li$$

$${}^{6}_{3}Li(n,\alpha)^{3}_{1}H$$

$${}^{3}_{2}He(n,p)^{3}_{1}H$$

(n,fission)

Desire high σ and high Q value

B-10 reaction

$$\underline{\text{Q-value}}$$

$${}^{10}_{5}\text{B} + {}^{1}_{0}\text{n} \rightarrow \begin{cases} {}^{7}_{3}\text{Li} + {}^{4}_{2}\alpha & 2.792\text{ MeV} \quad \textbf{(Ground state)} \\ {}^{7}_{3}\text{Li}^{*} + {}^{4}_{2}\alpha & 2.310\text{ MeV} \quad \left(\text{excited state}\right) \end{cases}$$

$$E_{\text{Li}} + E_{\alpha} = Q = 2.31\text{ MeV}$$

$$m_{\text{Li}} v_{\text{Li}} = m_{\alpha} v_{\alpha}$$

$$\sqrt{2 m_{\text{Li}} E_{\text{Li}}} = \sqrt{2 m_{\alpha} E_{\alpha}}$$

$$E_{\text{Li}} = 0.84\text{ MeV} \quad \text{and} \quad E_{\alpha} = 1.47\text{ MeV}$$

- B-10 is 19.8% abundant
- Excited state has an intensity of 94%
- Solve conservation of energy and momentum

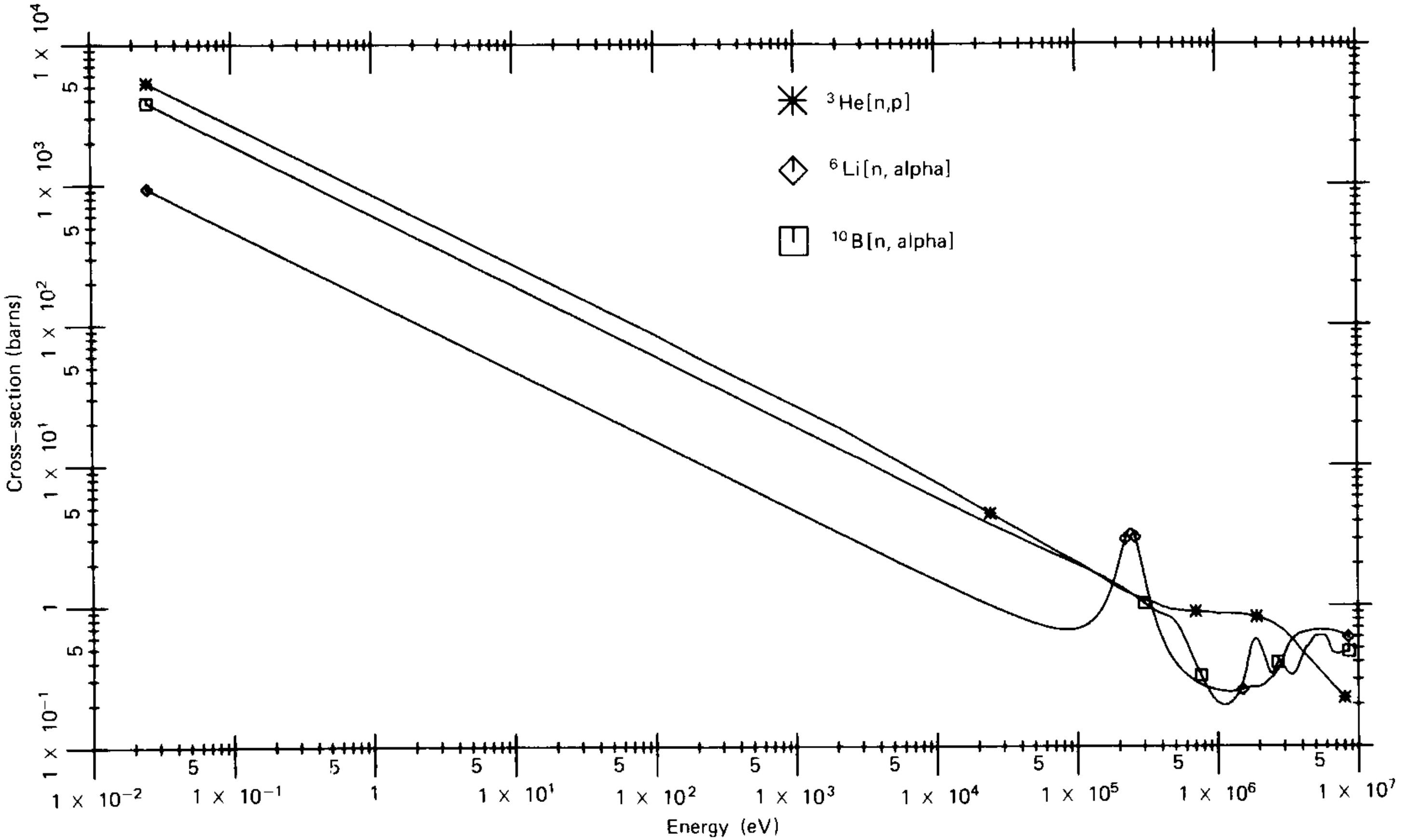
^{6}Li and ^{3}He reactions

$$ {}^{6}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{4}_{2}\alpha \qquad \frac{\text{Q-value}}{4.78\ \text{MeV}} $$

$$ {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{p} \qquad \frac{\text{Q-value}}{0.764\ \text{MeV}} $$

- High Q value of Li-6 is more desirable
- But absorption cross section is significantly higher for He-3 (5330 b vs. 940 b at thermal energy)

Reaction cross sections



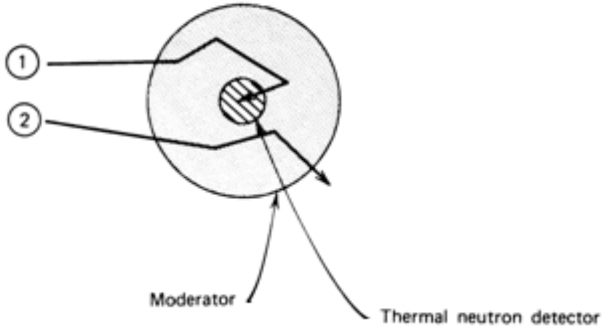
Fast neutron detection

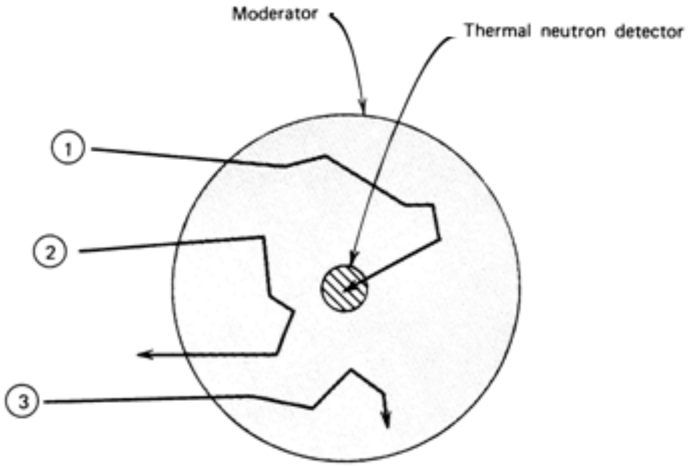
Three techniques for fast neutron detection

- Counters based on neutron moderation, i.e., slow down fast neutrons then detect them at energies where the cross section is high
- Detectors based on (n, c.p.) – “particle ejection” of short range heavy particle, e.g., α or p (transfer)
- Detectors utilizing fast neutron scattering

Technique #1

Moderated neutron detectors



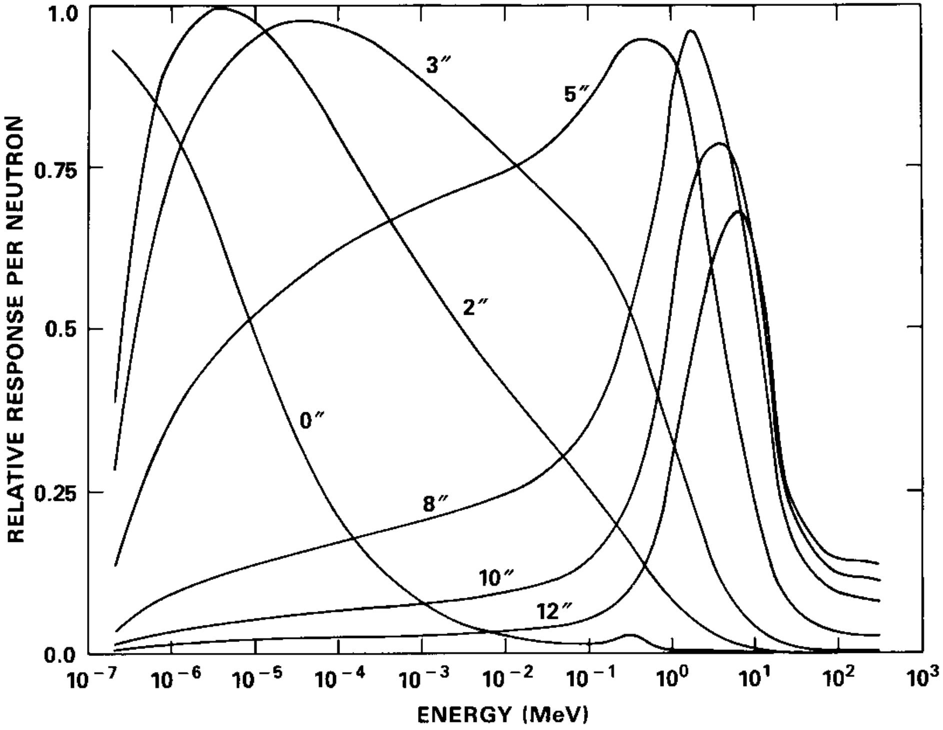


- Two different moderator thicknesses are shown; assume same fast neutron energies for representative neutrons 1, 2, and 3
- 1 is moderated and detected
- 2 is moderated and escapes, 3 is parasitically captured
- Larger moderators enhance 3 and reduce 2
- How does moderator size affect detection probability?

Moderating sphere

- At a given incident neutron energy, there's a moderating radius R that's just right to maximize detection efficiency, i.e., maximize the chance of 1 happening over 2 and 3
- Below the optimal R, detection efficiency is degraded by too many neutrons escaping while fast (Case 2)
- Above the optimal R, detection efficiency is degraded by losing too many neutrons to capture (Case 3) and leakage
- Conversely, a given fixed radius is optimal for detection of neutrons at some energy

Energy dependence of efficiency



- Efficiency plotted vs. neutron energy for spheres of many diameters

(n, c.p.) reactions used for detection

Technique #2

$${}^{6}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{4}_{2}\alpha$$

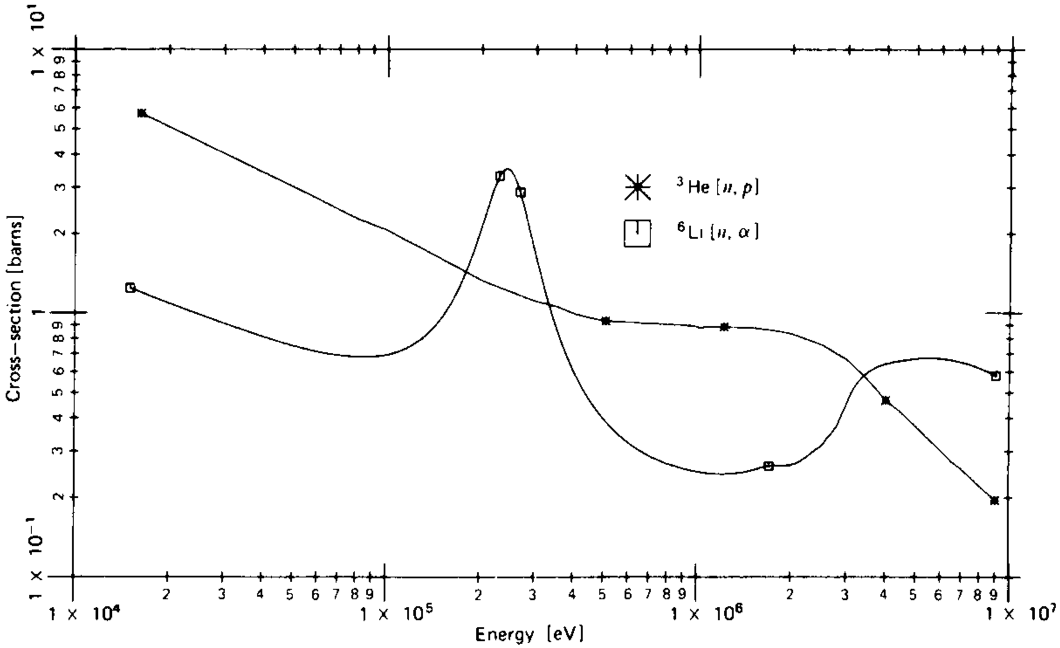
$$\underline{\text{Q-value}}$$
$$4.78\ \text{MeV}$$

$${}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{p}$$

$$\underline{\text{Q-value}}$$
$$0.764\ \text{MeV}$$

- These reactions are also used for fast neutrons
- While the Q-value is the same as thermal case, the measured energy is equal to the sum of the Q-value and the fast neutron energy deposited in the detector

Fast neutron cross sections



- Cross sections are 10^3 lower than in slow neutron range
- Lower count rates result

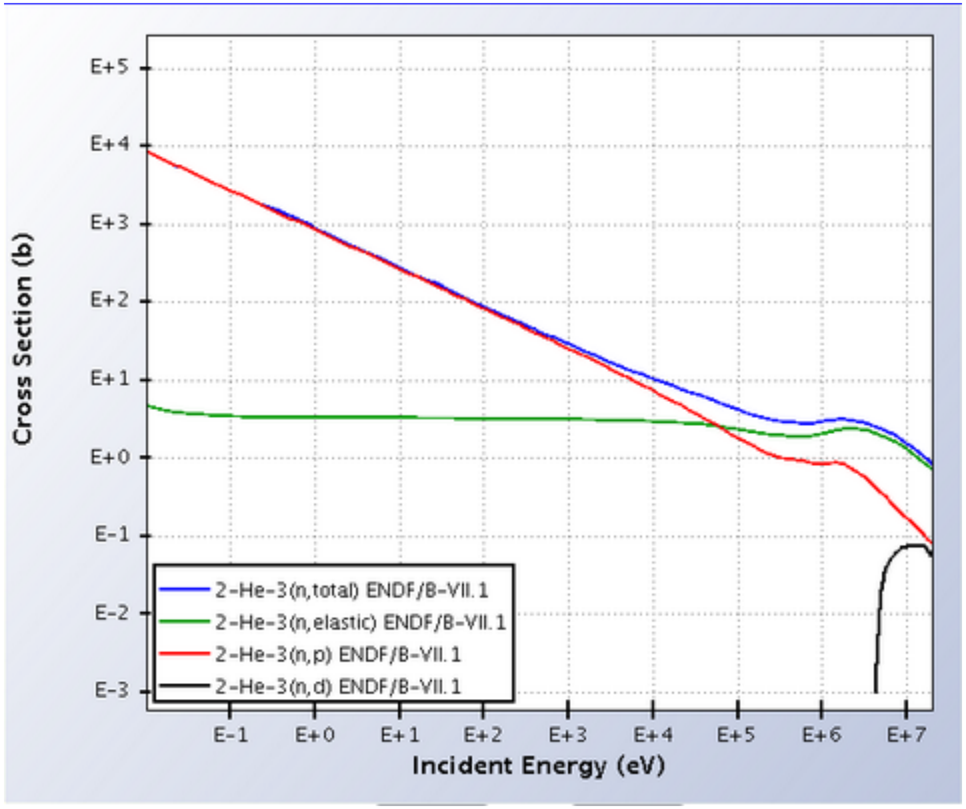
Example: He-3 gas proportional tube

$${}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{p} \qquad \frac{\text{Q-value}}{0.764\ \text{MeV}}$$

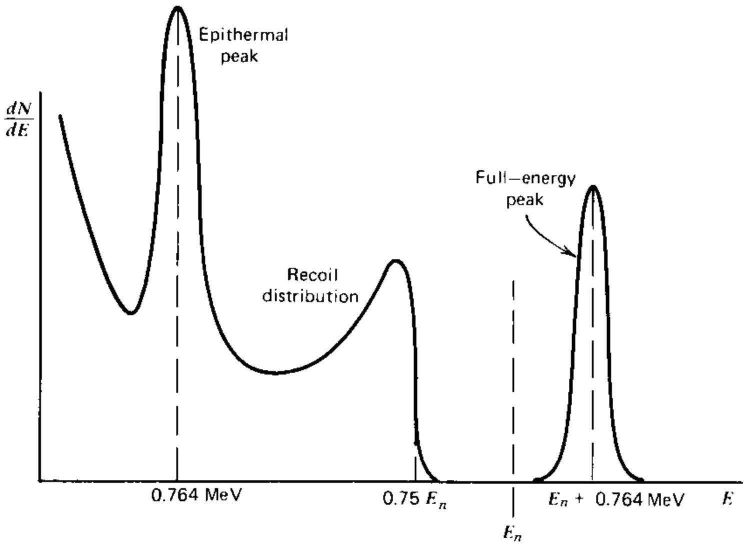
- Gold standard for slow neutron production but no longer sexy
- Fast neutrons < 10 MeV are likely to deposit energy inside a He-3 tube in one of three ways:
  - The desired (n,p) reaction where n is fast
  - Elastic scattering off of He-3
  - The (n,p) reaction where n has been slowed down in surrounding materials
- Gamma rays may also interact inside detector wall, resulting in low probability of detection
- Rise time discrimination is used to reject all but (n,p)

Reaction detail in ^{3}He gas

- ^{3}He
  - Cross section is 1/v
  - Thermal neutrons
  - Scattering > (n,p) above 100 keV
  - Scarce material



Ideal He-3 tube pulse height spectrum



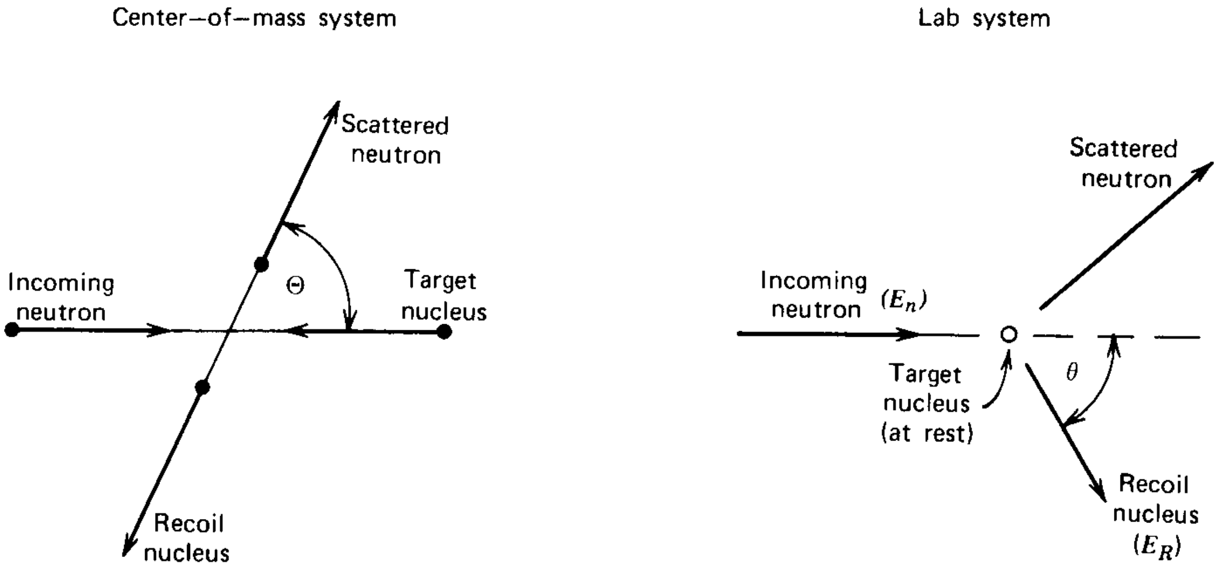
- Assume neutron source is monoenergetic, energy E_n
- Full energy peak due to (n,p) reactions of source
- Recoil distribution due to elastic scattering off of He-3; max at $0.75E_n$
- Epithermal peak due to thermalized neutrons undergoing (n,p) reaction
- Neutron energy E_n would then be found by subtracting Q from full-energy peak

Fast neutron measurements based on elastic scattering

Technique #3

- Neutron collision transfers part of its kinetic energy to nucleus of detector atom, forming a *recoil nucleus* that is now "visible" as an ionizing particle
- When the atom consists of hydrogen, this process forms a *recoil* proton
- Then it is possible to transfer up to the full neutron energy in a single elastic scattering collision
- Detector types: organic scintillators (plastic, liquid)

Kinematics of neutron elastic scattering



- Collision seen in two frames of reference
- Let *A* = target nucleus mass
- Apply conservation of energy and momentum

Elastic scattering kinematics

$$E_R = \frac{2A}{(1+A)^2}(1-\cos\Theta)E_n$$

$$\cos\theta = \sqrt{\frac{1-\cos\Theta}{2}}$$

$$E_R = \frac{4A}{(1+A)^2}(\cos^2\theta)E_n$$

Energy given to nucleus is uniquely determined by scattering angle

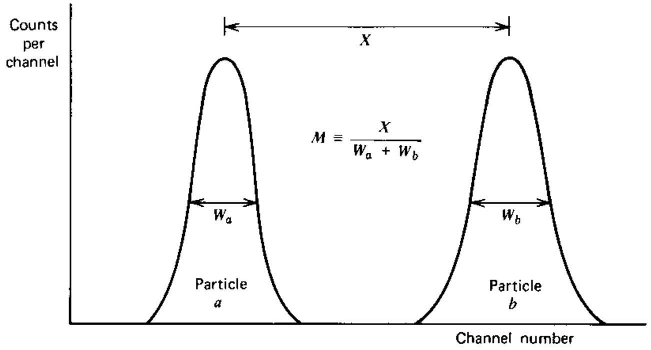
For a head on collision, max recoil energy is

$$\boxed{E_R\big|_{\max} = \frac{4A}{(1+A)^2}E_n}$$

A	$E_R\big\|_{\max}$	
1	E_n	**Hydrogen**
3	$0.75E_n$	**He-3**
12	$0.28E_n$	

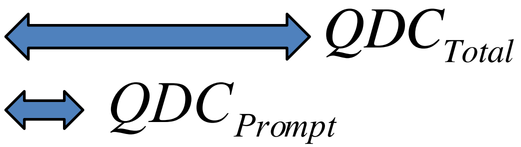
Pulse shape discrimination

- Aside from linear pulse amplitude and time of occurrence, sometimes pulse shape carries useful information
- Two general approaches to PSD
  - Electronic methods for sensing rise time differences
  - Derive a signal based on integrating total charge over two different time periods
    - Take a ratio of the two integrals
    - Distribution shown at right takes form
    - Characterize by figure of merit M



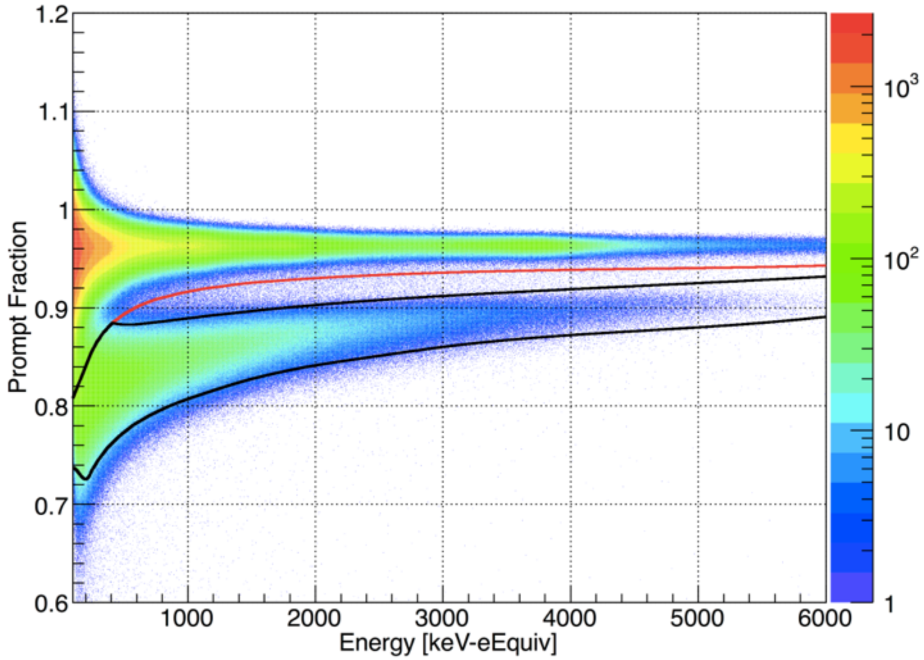
- Example: Gamma/neutron discrimination of liquid scintillators

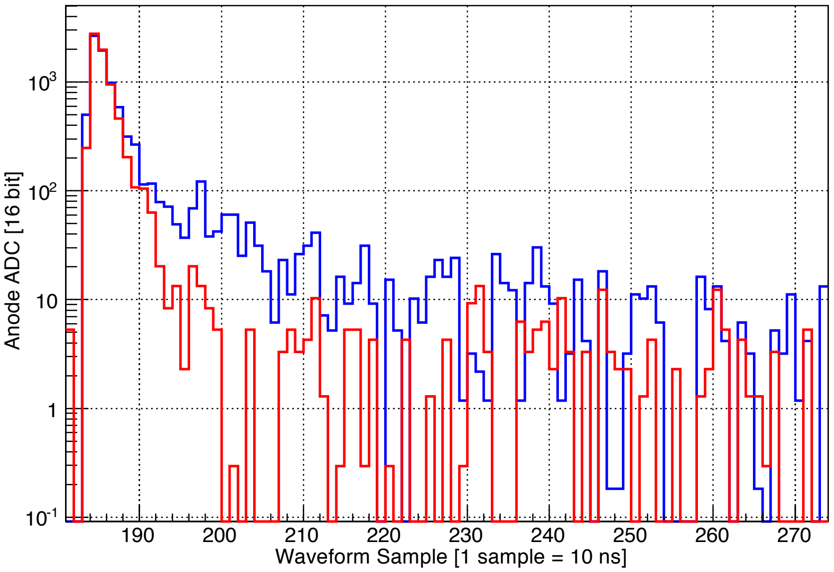
$$PSD \equiv \frac{QDC_{Prompt}}{QDC_{Total}}$$

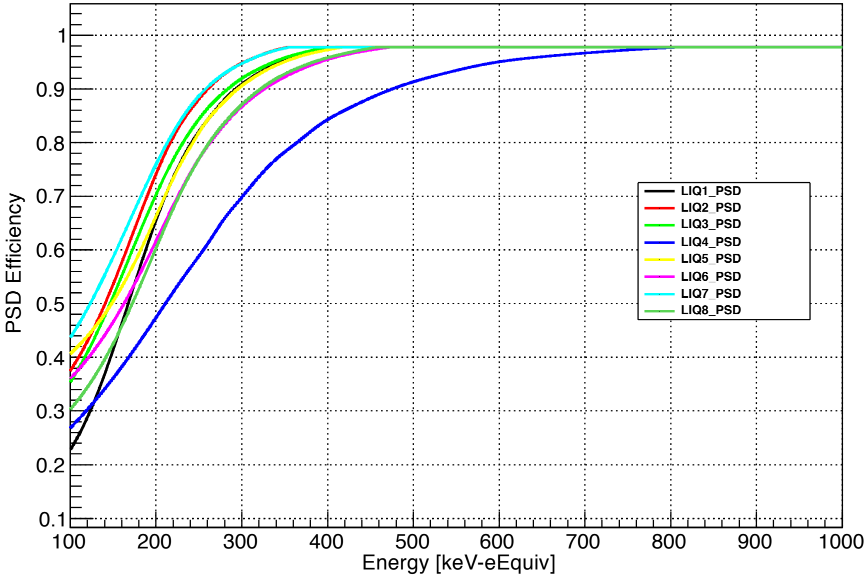


QDC_{Total}

QDC_{Prompt}





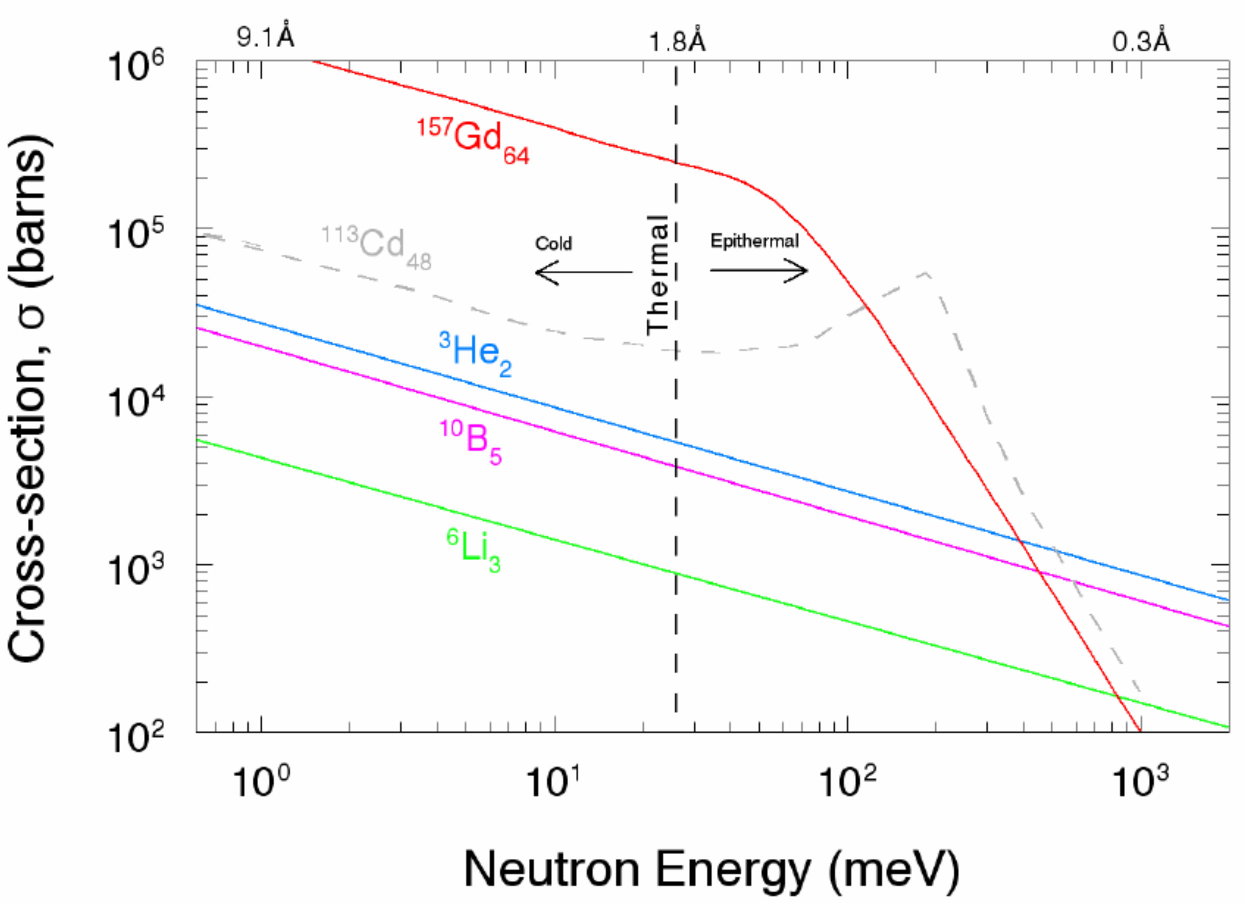


Some other neutron detection methods

- Capture gammas: Foils, semiconductors, scintillator
- Induced radioactivity: Foils, foil/scintillator sandwich, scintillator
- Radiation damage: Tracks, dosimeters
- Recoil + capture (Capture gated spectrometer): B-loaded scintillator
- Heat: Bolometer, bubble dosimeter

More relevant cross sections

More reaction cross sections



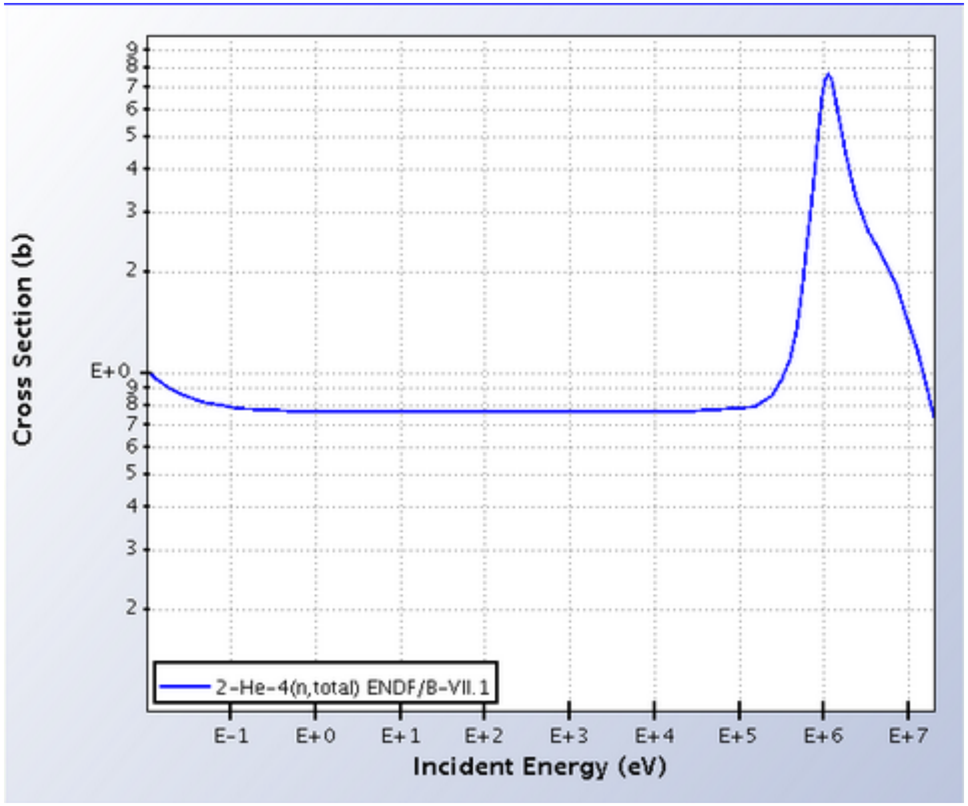
- 1 Å ~ 81.8 meV ~ 3956 m/s

Neutron reactions in ^{1}H gas

- Hydrogen
  - Cross section is fairly constant over a large energy range
  - Cross section is fairly large
  - No resonances
  - Highest energy transfer (1:1)
  - ~50,000 e^-/MeV
  - Use with noble gas to drive scintillation
  - Use in proportional gas to detect charge

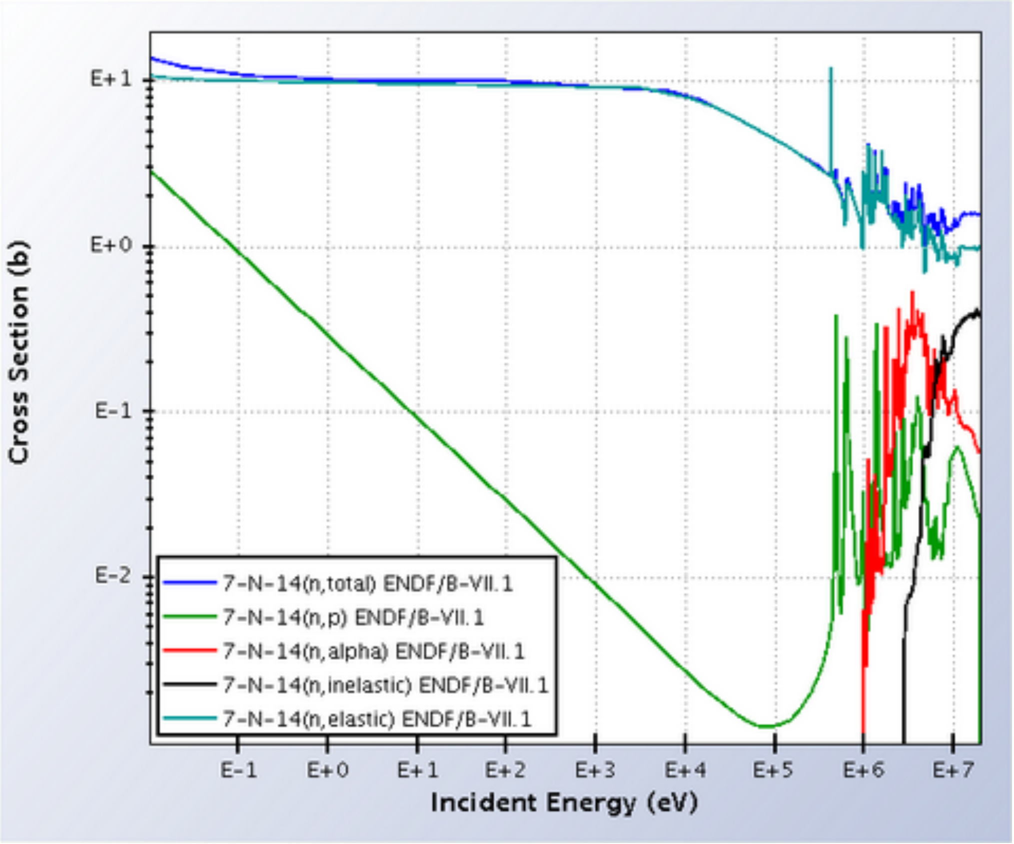
The ^{4}He alternative

- ^{4}He
  - Need high pressure
  - FAST neutrons
  - Maximum recoil energy is 64% of incident energy
  - UV scintillator
  - Good proportional gas



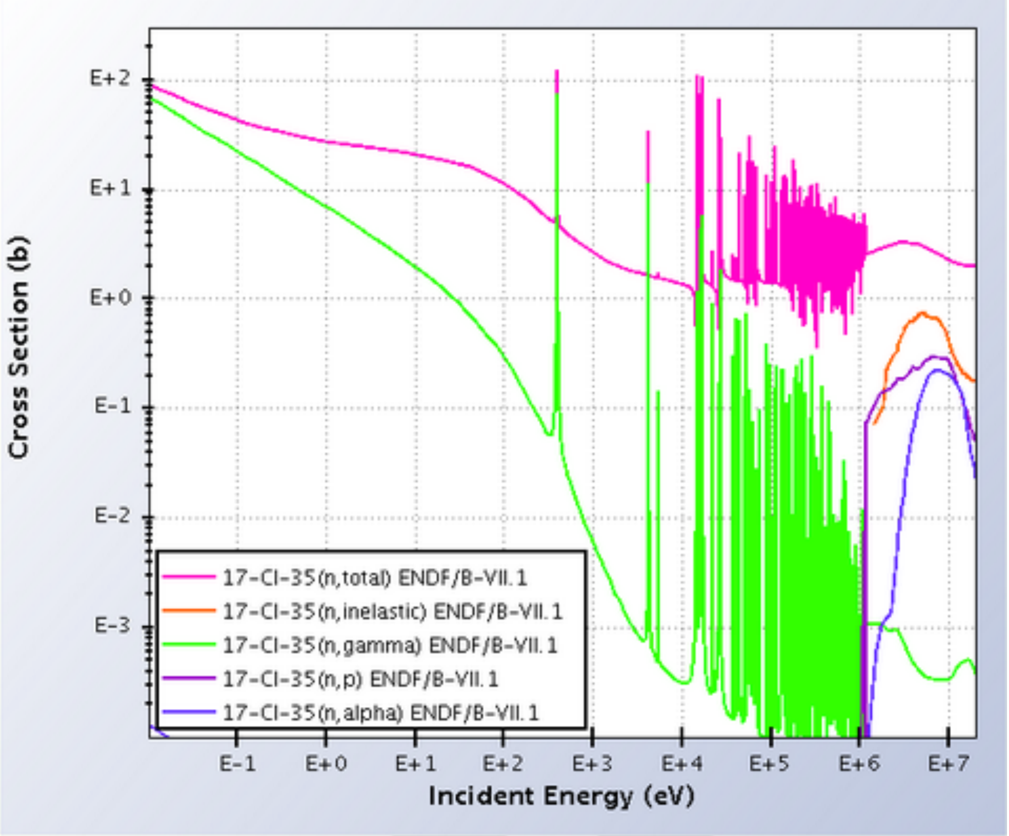
Neutron reactions in gas

- ^{14}N
  - (n,p) is 1/v
  - Useful only at thermal energies
  - May be used in reactor instrumentation



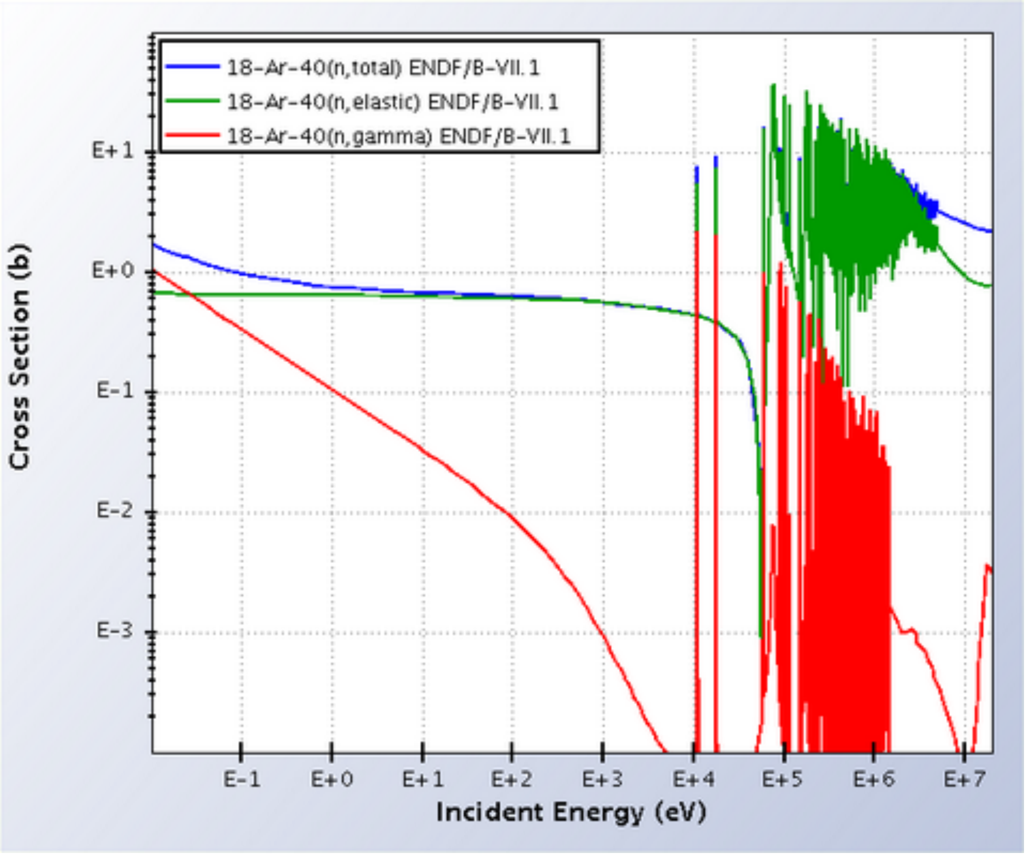
Neutron reactions in gas

- ^{35}Cl
  - Many resonances
  - (n,γ) dominates at low energies
  - (n,p), (n,α) important above 1 MeV
  - Inelastic gammas produced, too



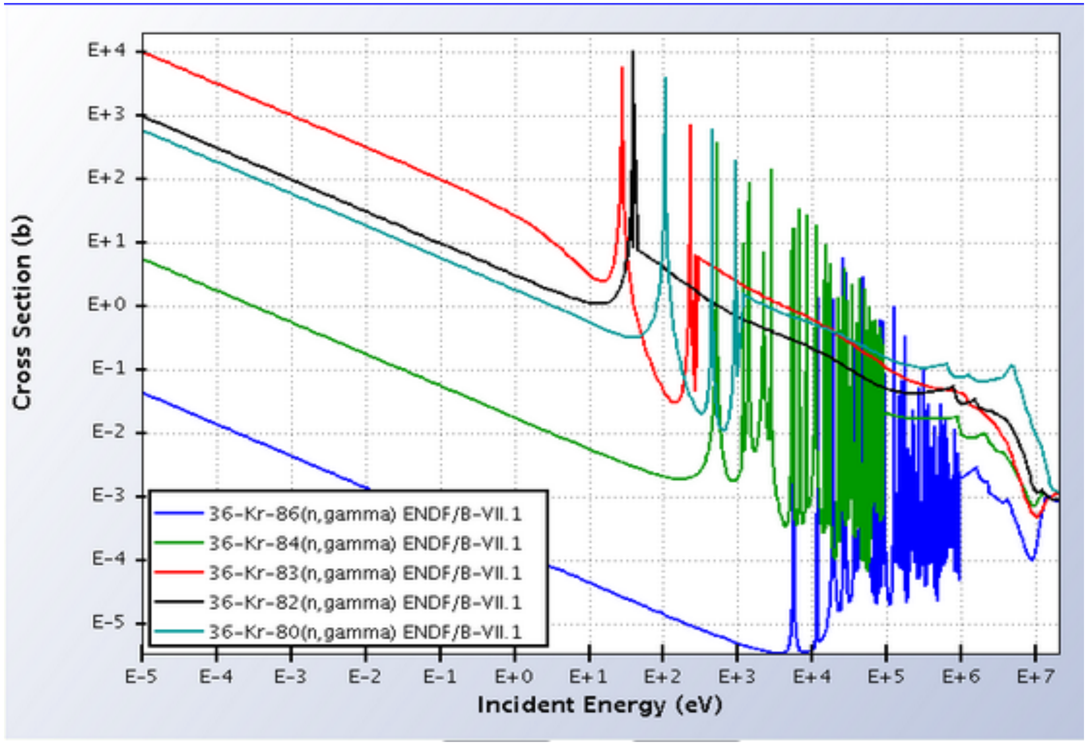
Neutron reactions in gas

- ^{40}Ar
  - Many resonances
  - (n,g) interesting at thermal energy
  - cp reactions tiny



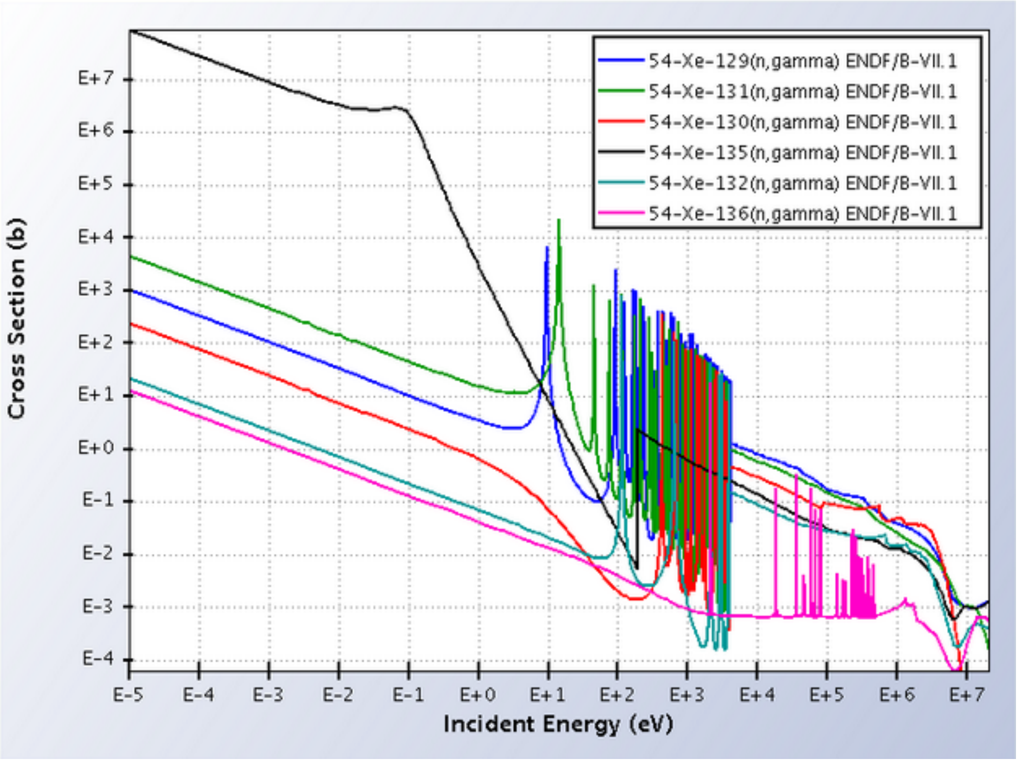
Neutron reactions in gas

- Kr
    - Many isotopes
    - (n,cp) tiny
    - Capture is dominant



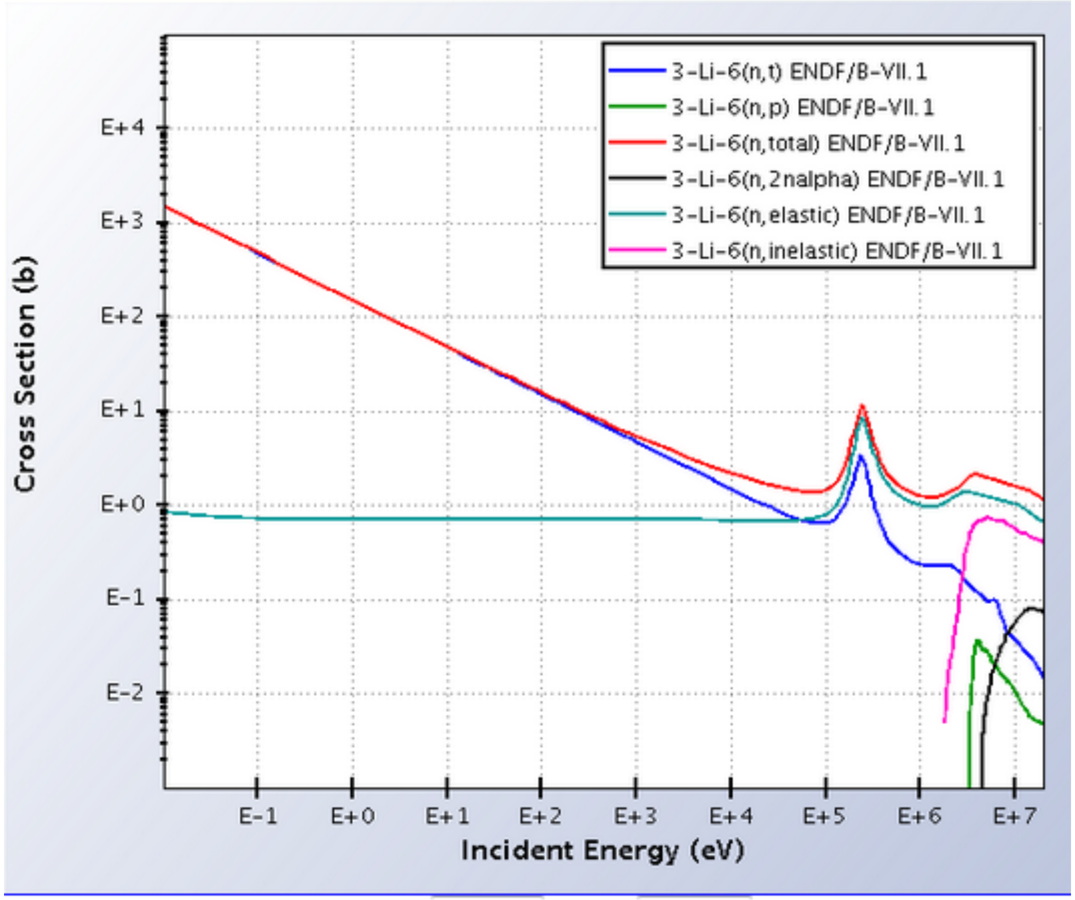
Neutron reactions in gas

- Xe
  - Many isotopes
  - (n,cp) tiny
  - Capture is dominant
  - Z is sufficiently high that γ spectroscopy is possible

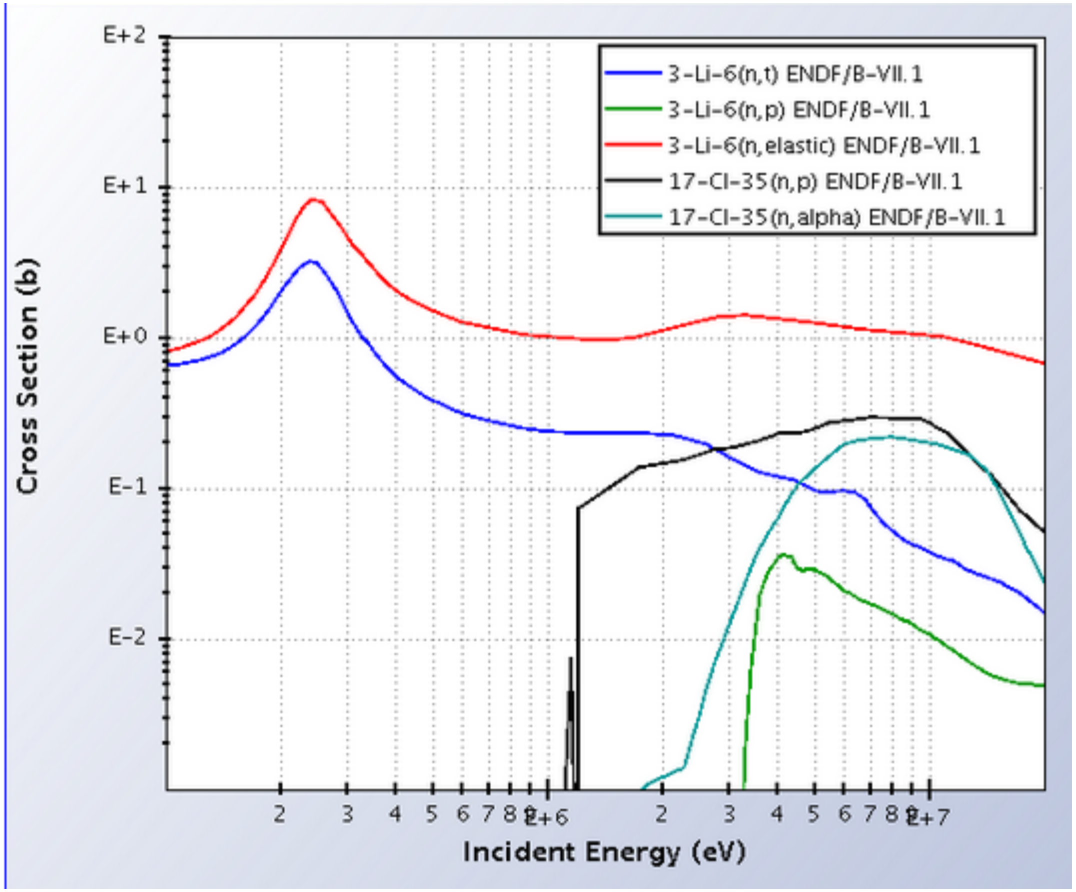


Neutron reactions in gas

- ^{6}Li
  - 1/v cross section
  - (n,t) is dominant
  - Elastic, inelastic, and break-up > (n,t)
  - Resonance at 250 keV seen in (n,t) and scattering



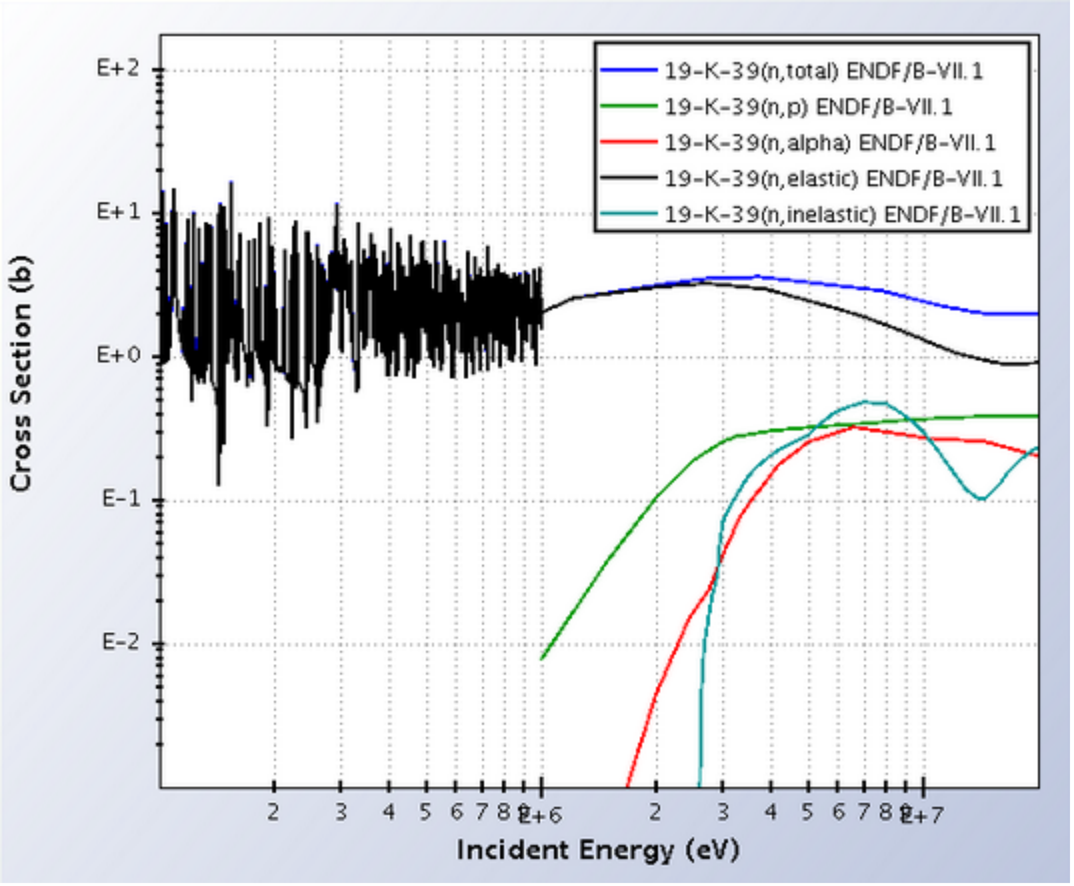
^{6}Li and ^{35}Cl cross sections together



- Li elastic ≈ 3-6x Cl cp cross sections
- Li reactions compete with Cl
- Cl reactions compete with each other
- e.g., CLYC scintillator

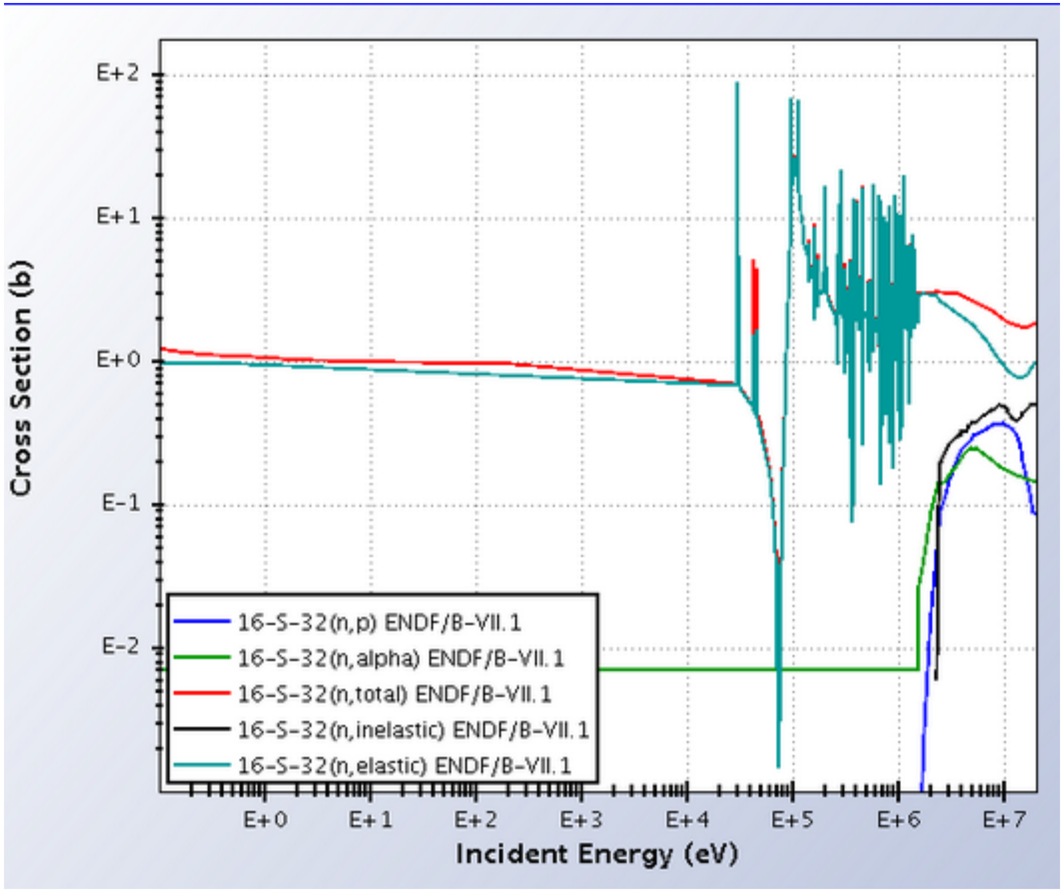
Fast neutron cross sections

- ^{39}K
  - Similar behavior to ^{35}Cl
  - Inelastic scattering competes with cp reactions



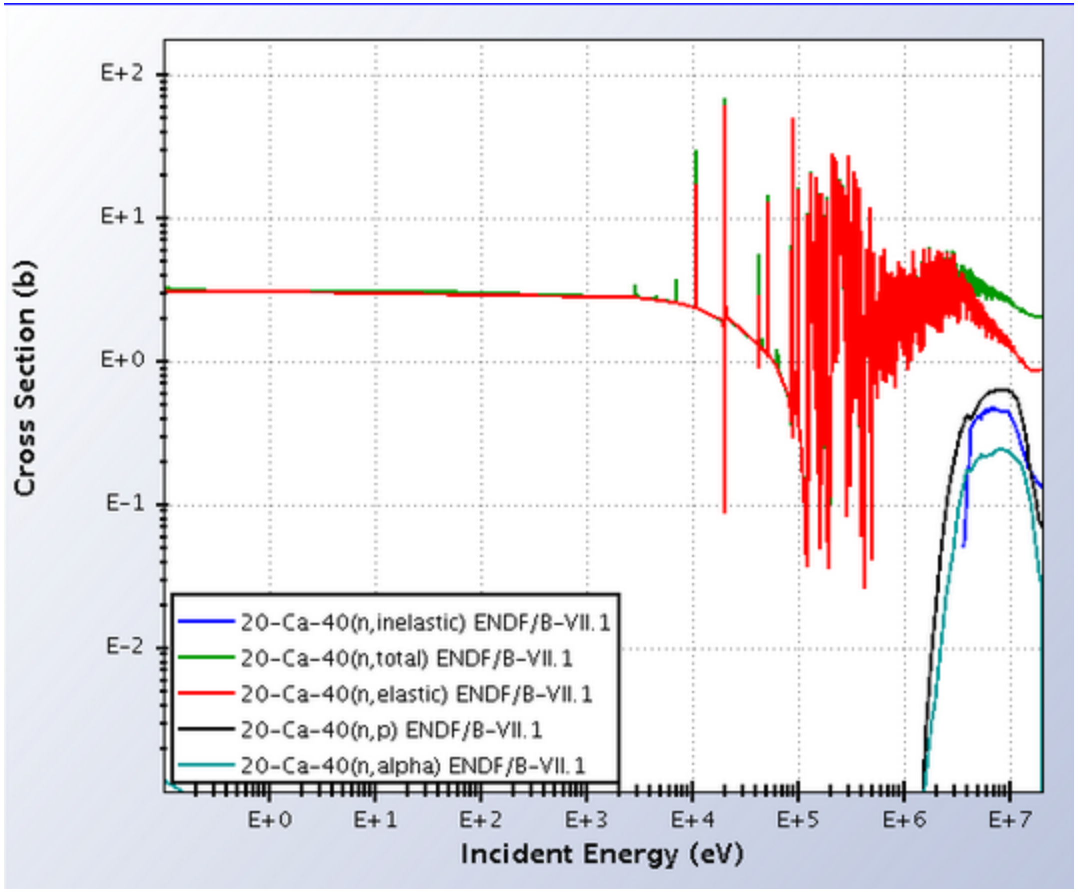
Fast neutron cross sections

- ^{32}S
  - Similar behavior to ^{35}Cl
  - Inelastic scattering competes with cp reactions

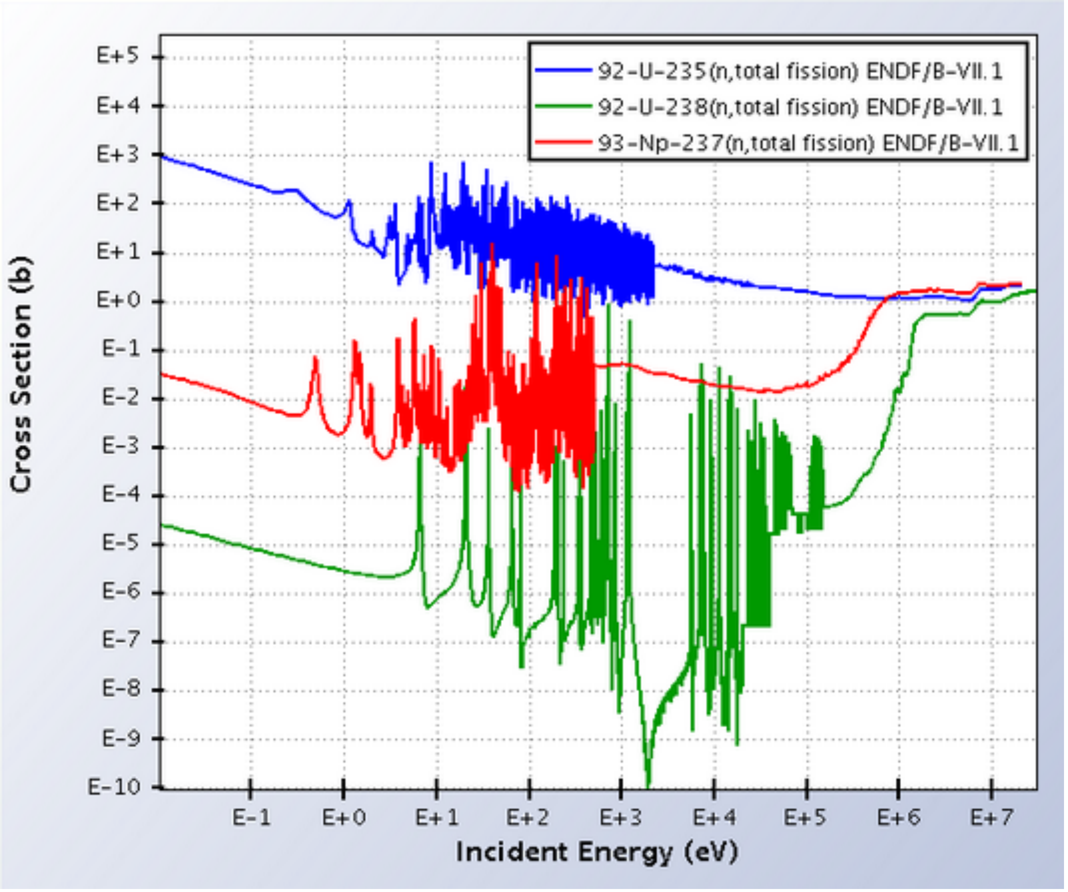


Fast neutron cross sections

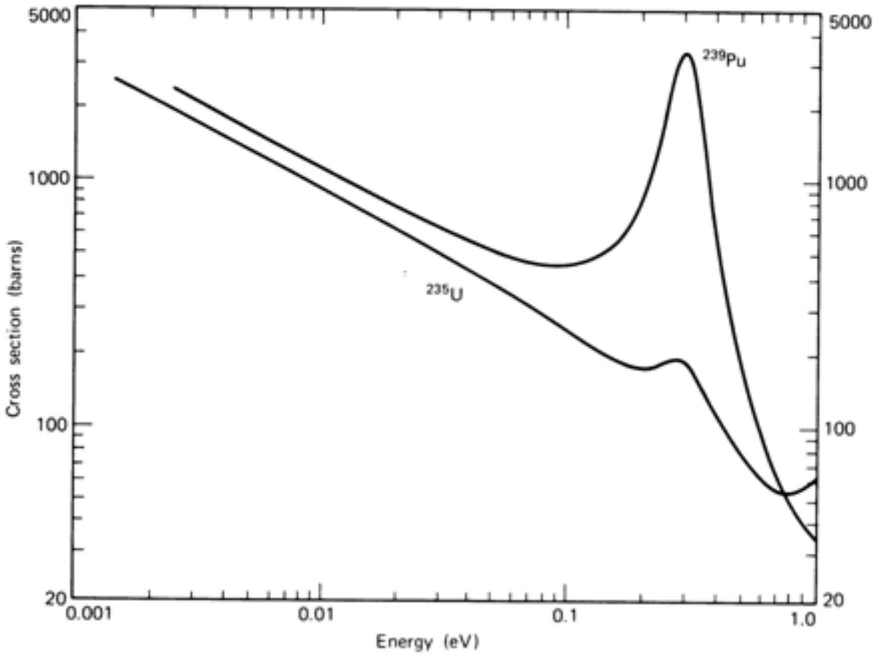
- ^{40}Ca
  - Similar behavior to ^{35}Cl
  - (n,p) favored slightly

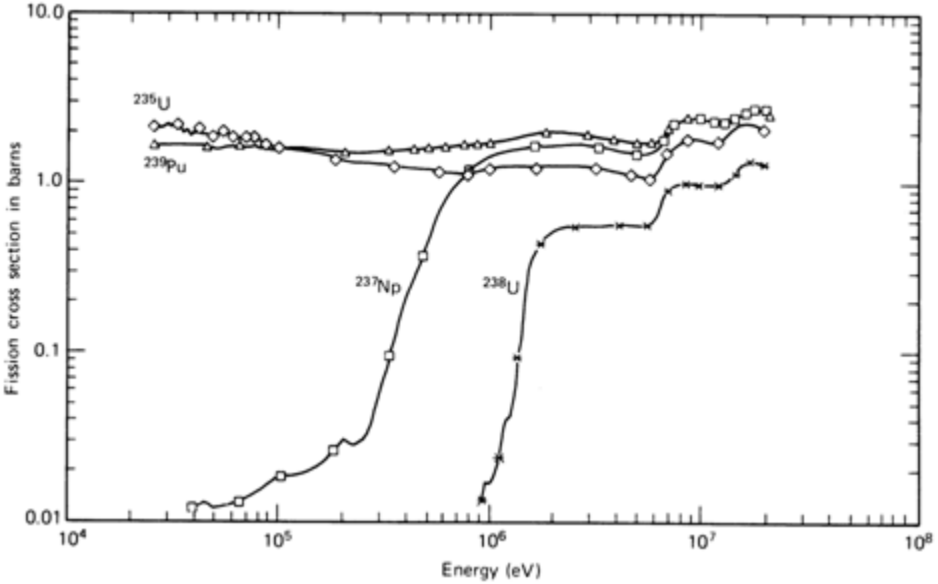


Fission cross sections



Fission cross sections

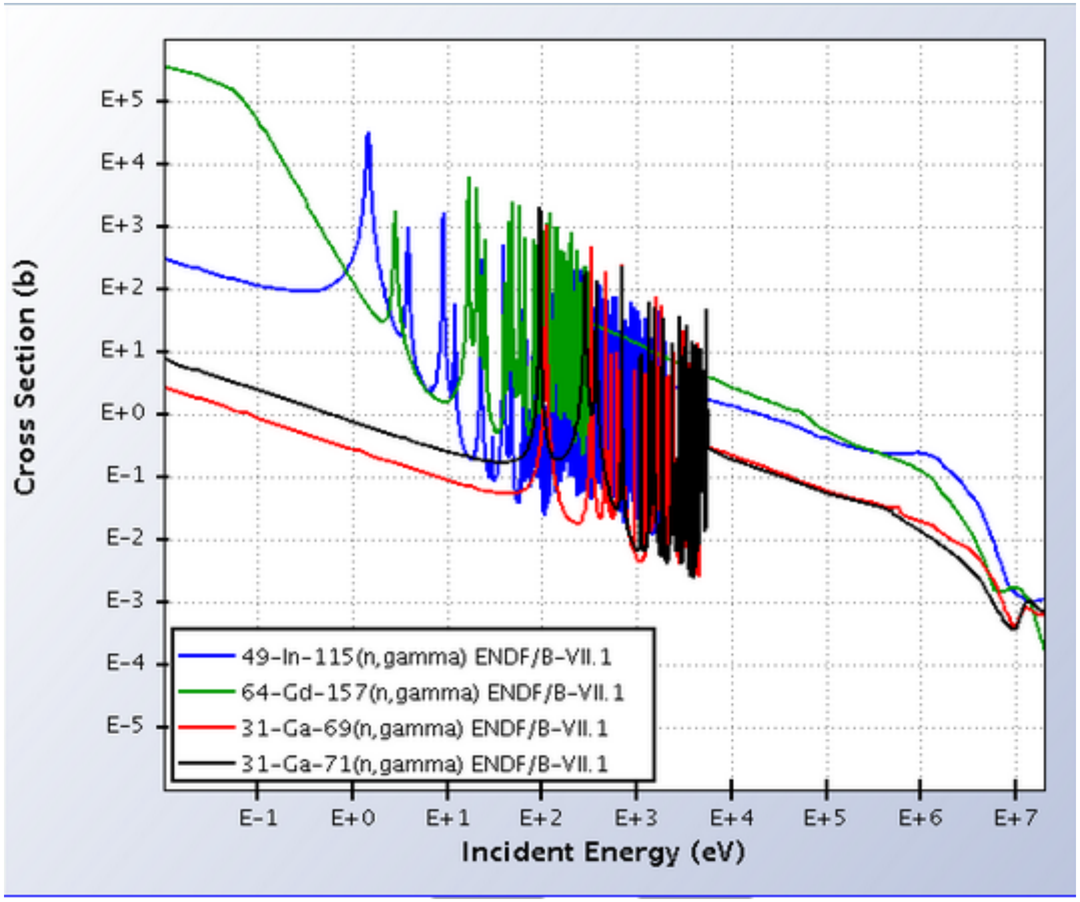




- Fission cross sections shown for fissile materials in slow and fast regions
- Np-237 and U-238 are used as threshold detectors sensitive only to fast neutrons

Cross sections relevant to glass Cherenkov detectors

- Need radioactive beta and/or energetic γ that will yield Cherenkov radiation



Summary

- A lot of interesting science with neutrons has happened since it was discovered only eighty some years ago; here we have just scratched the surface
- We looked at many of the different ways neutrons could interact with matter, including a look at some specific cross sections
- We began to look at how observation of these reactions can be used as a tool to better understand nuclear properties
- We begun to examine how radiation and especially neutrons, both slow and fast, may be detected and measured
- We have begun to consider applications in nuclear physics and neutron science; nuclear security and nonproliferation technologies did not make the list this year… possibly topic for next year?

Thanks for your invitation!

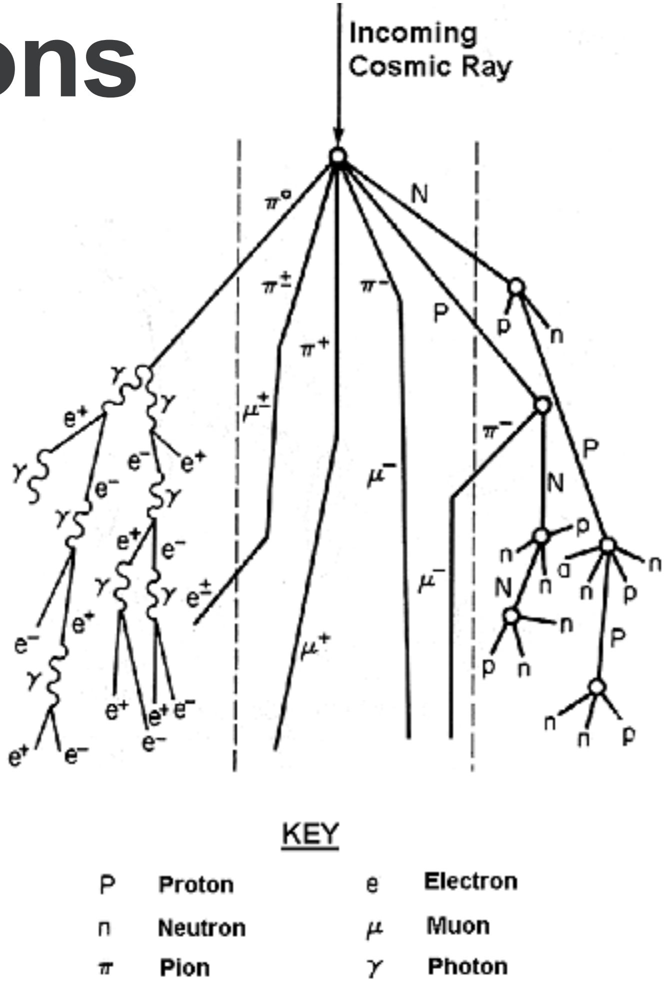
Appendix:

A few application slides relevant to neutron detection for nuclear security and nonproliferation

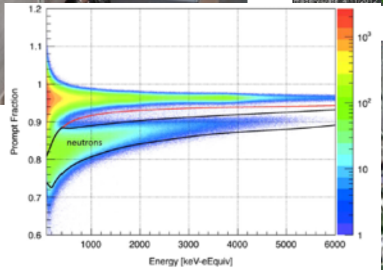
Fast neutron applications

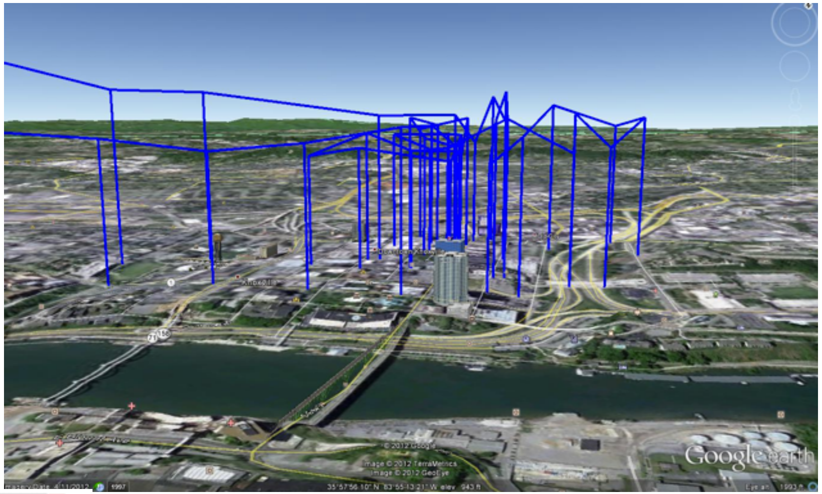
Cosmic ray interactions

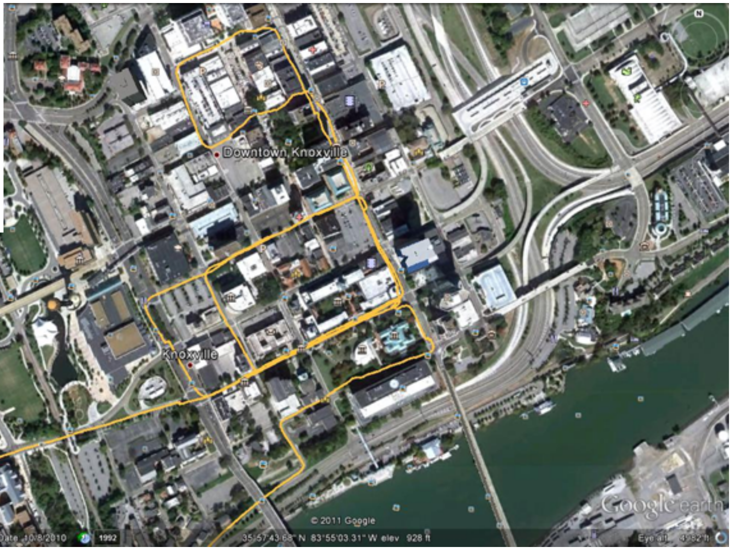
- Electromagnetic/soft component
- Meson/hard component: Pions and kaons tend to decay into muons
- Nucleonic component
  - High energy (> 20 MeV) neutrons produced by cascade interactions and projectile fragmentation
  - Lower energy (< 20 MeV) neutrons produced by target evaporation and moderation of high energy neutrons in local materials



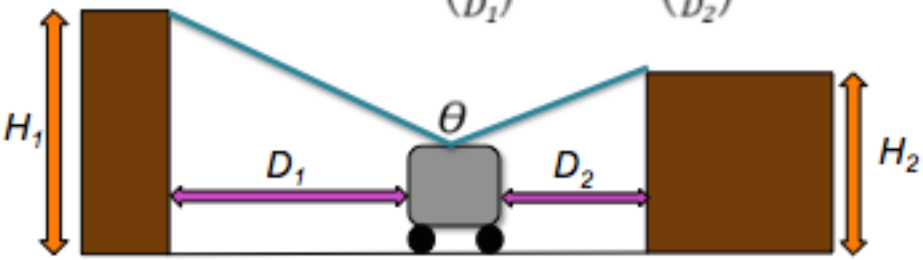
Mobile neutron background analysis



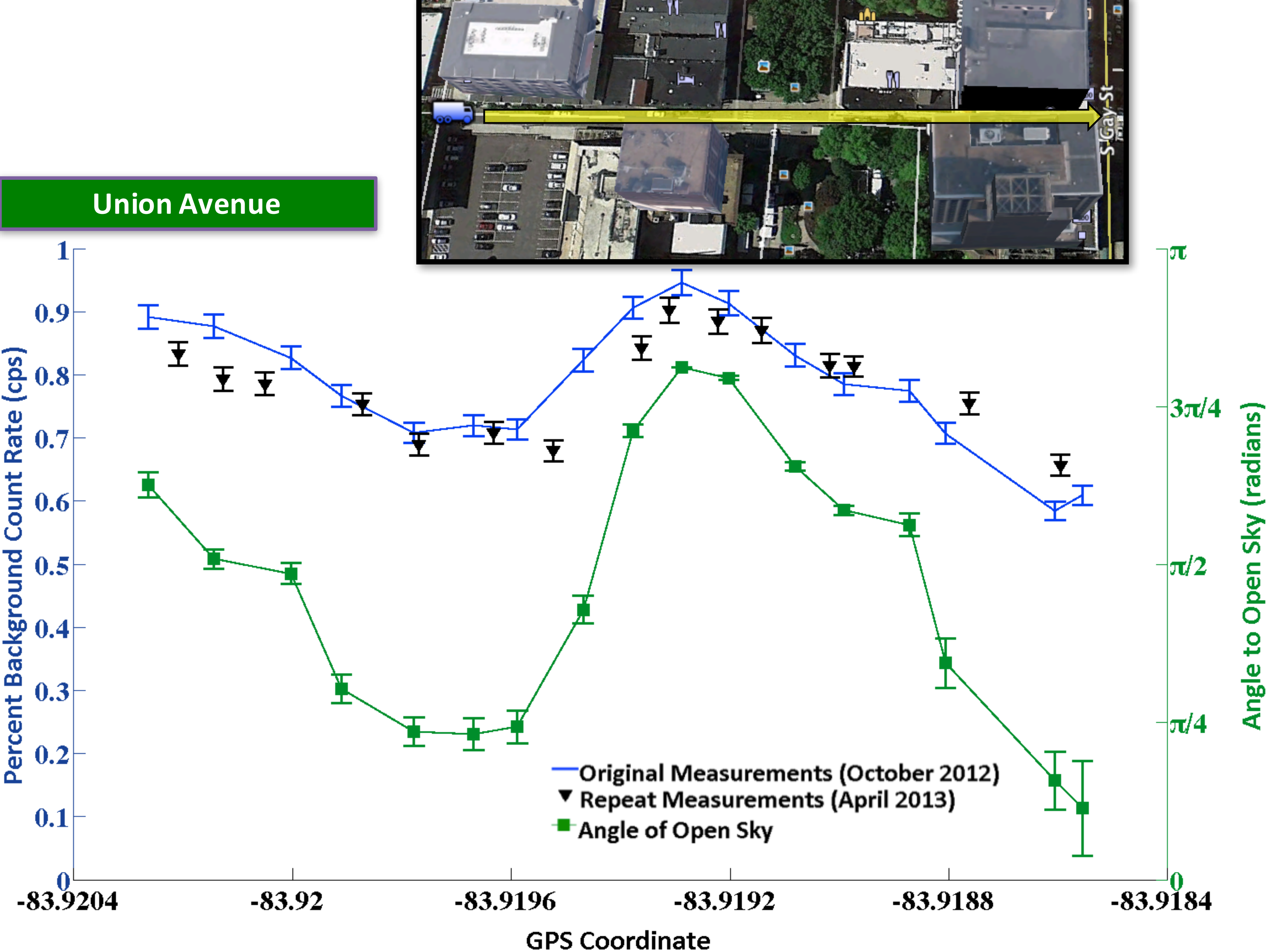




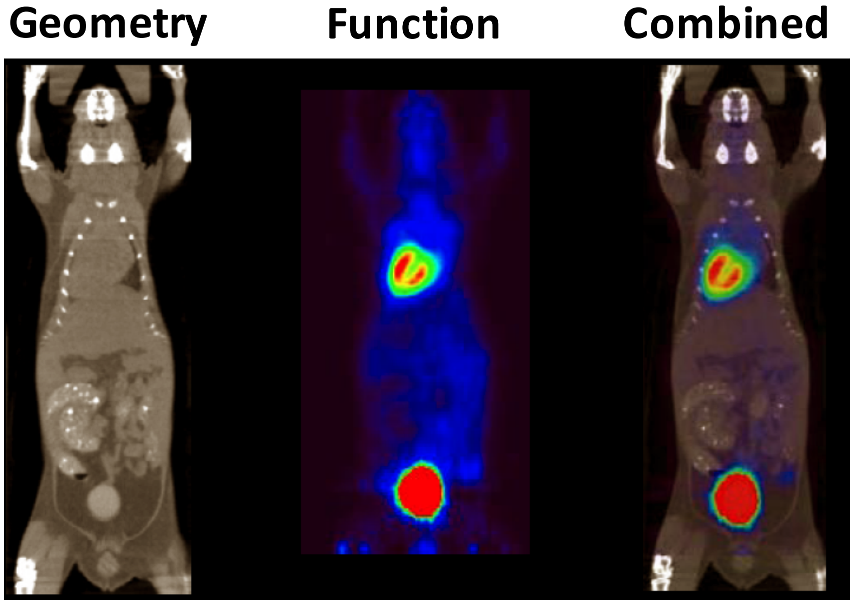
$$\theta = \pi - \tan^{-1}\left(\frac{H_1}{D_1}\right) - \tan^{-1}\left(\frac{H_2}{D_2}\right)$$



Union Avenue



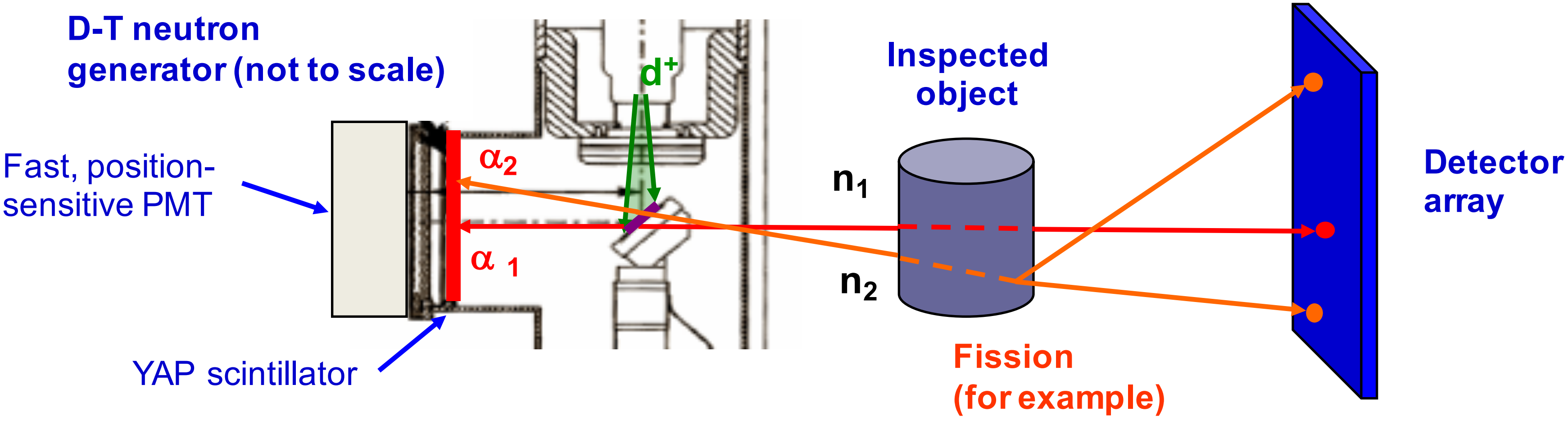
Anatomical and functional imaging



Example co-registered CT and PET (Siemens)

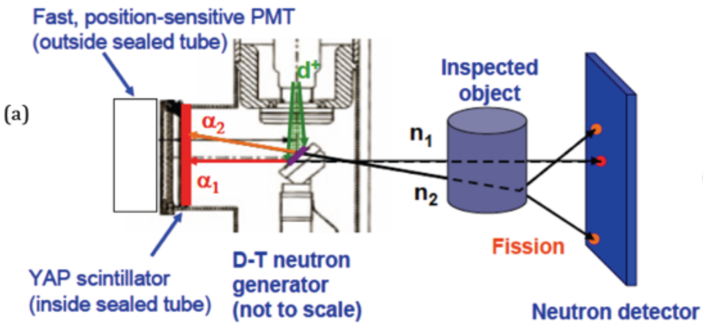
- Imaging modalities such as PET and CT frequently combined to give both anatomical and functional information (e.g., to image the metabolism of glucose)
- Analogously, neutron transmission imaging (anatomical) can be combined with induced particle or scattered neutron imaging (functional)

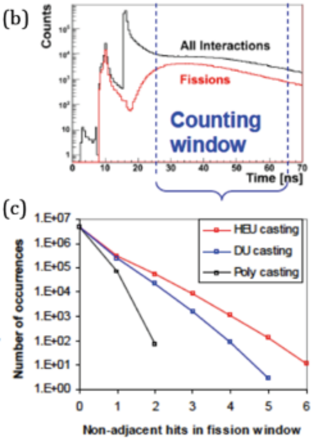
Imaging with tagged neutron interrogation

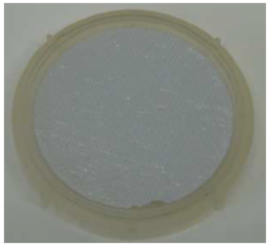


- Fast-neutron transmission gives basic material configuration, and induced particle or scatter image helps identify nuclear material and shielding
- Time and direction of interrogating neutrons are known from associated alpha particle of the $d + t \rightarrow \alpha + n$ reaction
- These sources are portable, have good neutron emission, and emit neutrons that have good penetrability in high-Z materials

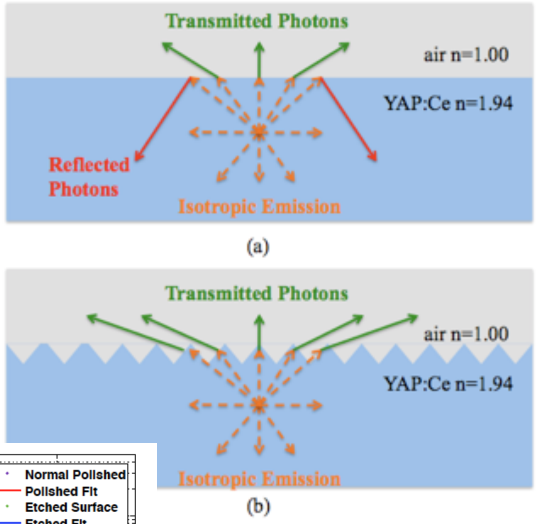
Instrumentation for tagged neutron interrogation







Associated particle detector

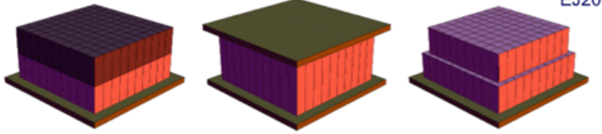


Neutron block detector

Emission and absorption spectra musn't overlap (unlike most fast plastic scintillators)

Best measurement of 185 ps FWHM with EJ200

Our best measurement wa 729 ps FWHM with 2 layers of EJ200

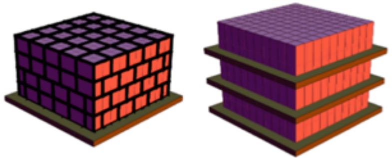


(a) Phoswich design

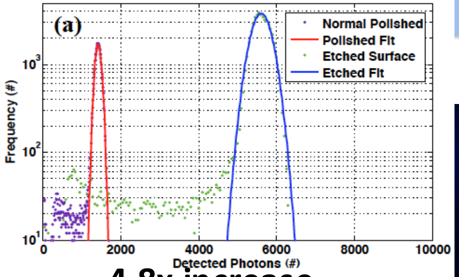
(b) Double-sided readout

(c) Stacked layers with a relative displacement with respect to each other

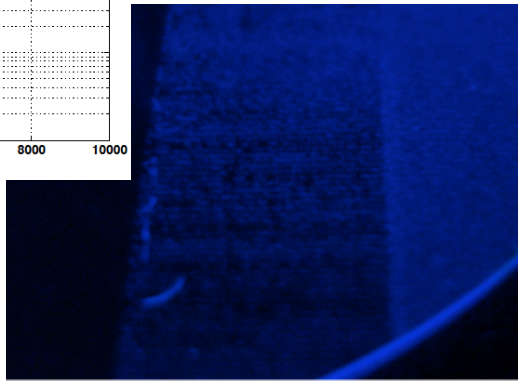
More fabrication cost compared with similar method (c), not yet investigated



Brute force method, most expensive, not yet investigated

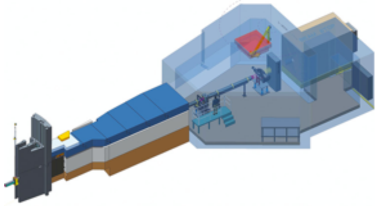


4.8x increase



Slow neutron application

High resolution neutron imaging for neutron science



VENUS:
Versatile Neutron Imaging Instrument at the Spallation Neutron Source

Lithium-6 Scintillator Fiber Optic Array, 500nm - 1um channels

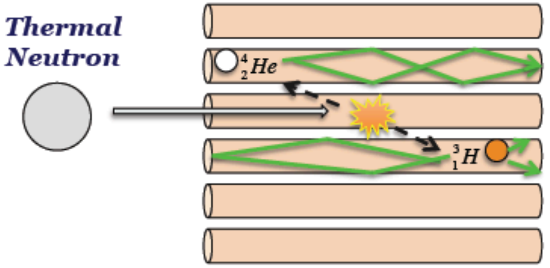


Image Intensifying CCD

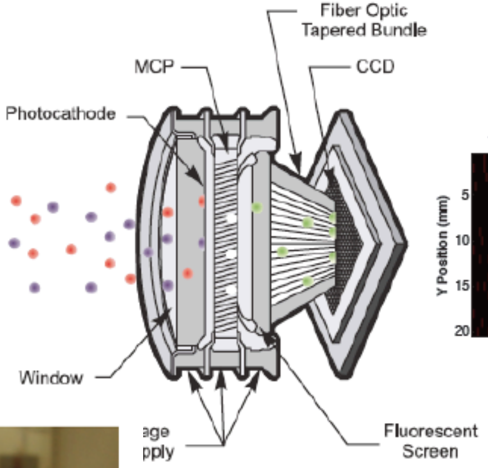


Image Charge Tracks Reconstruction